A Methodology for Earthquake Risk Mitigation of Hospital Systems

Dissertation

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by

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*) Either the German or the Italian form of the title may be used.

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Goslar - August 25, 2012.

to my grandma Dina.

to Amelie,
we are a small family now!

and most important to Sara,
to our promise.

…and to myself.

Abstract

Aims

As it represents the final point of the whole rescue chain, hospital infrastructure is one of the most important elements of medical response to earthquakes. In order to correctly manage the emergency by providing the most efficient medical response, it is fundamental to carry out a simple, rapid and reliable risk assessment of seismic impact on hospitals. The purpose of this work was to develop a decision support system for helping the decision makers with the seismic risk mitigation of health structures.

Main Findings

A new integrated methodology was designed to identify vulnerabilities in the hospital based on a combination of two main research approaches: the theory of complex systems (input-output inoperability model of Leontief and the Fault Tree Analysis) and the rapid seismic vulnerability assessment (field evaluation forms). After a first risk assessment based on hospital safety and coping capacity at the OSMA Florence Hospital, the model was validated with a real past event (L'Aquila earthquake in 2009, Italy) and, finally took into consideration the risk mitigation phase at the Santa Clara Valley Medical Center in California, US.

The model application found out that the Leontieff model is less robust and reliable than FTA especially for high seismic intensity scenarios. The risk mitigation phase showed that the structural interventions (Florence at M=6 and US at M=8) did not add any further appreciable improvements to the non-structural actions. Moreover, the Italian hospital could provide a proper coping capacity by simultaneously applying fixing actions on both elements, basic installations and medical equipment. While for the indirect measures (medical mobile unit installation and patients' air evacuation), the US case would need less external facilities and support than OSMA.

Conclusions

The results of the study serve as a support to decision makers for seismic risk mitigation of modern health structures (US and Europe case studies) by providing a software prototype able to simulate the effects and evaluate the cost of applying different retrofitting actions. Furthermore, the new approach took into account both the strategic and sheltering functions of health structures by using quantitative indices such as the HTC (Hospital Treatment Capacity) and the new index IS (Intrinsic Security).

Riassunto (ITA)

Obiettivi

La struttura ospedaliera è uno degli elementi essenziali della risposta medica territoriale durante un sisma in quanto rappresenta il punto finale della catena di salvataggio. Al fine di pianificare e gestire correttamente l'emergenza, è quindi fondamentale effettuare una valutazione semplice, rapida ed affidabile del rischio sismico che consideri anche, ma non solo, l'aspetto strategico e funzionale dell'ospedale. Lo scopo di questo lavoro è stato quello di progettare un sistema di supporto decisionale per fornire ai decisori ospedalieri le informazioni e le soluzioni interventistiche più appropriate, inclusi i costi, per la riduzione del rischio sismico.

Principali risultati

Una nuova metodologia integrata è stata sviluppata per valutare il rischio sismico in ospedale attraverso la combinazione di due principali approcci scientifici: la teoria dei sistemi complessi e le metodologie relative alla valutazione rapida. Dopo una prima applicazione metodologica effettuata presso l'ospedale di Firenze OSMA, il modello è stato validato con un caso reale passato fornito dall'ospedale San Salvatore delL'Aquila durante il terremoto del 2009. Infine, anche con l'obbiettivo di coprire la più vasta gamma di ospedali moderni, il modello validato è stato applicato ancora ad OSMA ed al Santa Clara Valley Medical Center (SCVMC) in California negli Stati Uniti. Tra i principali risultati si ha che il modello di Leontieff risulta essere è meno robusto ed affidabile rispetto all'analisi FTA, soprattutto per scenari ad alta intensità sismica (I>8). La fase di riduzione del rischio sismico (I=6 OSMA e I=8 SCVMC) ha mostrato come tra gli interventi diretti, quelli strutturali non aggiungano alcun miglioramento apprezzabile agli effetti forniti dalle azioni non strutturali. Inoltre, l'ospedale italiano necessità di entrambe le azioni di retrofitting non strutturale (impianti tecnici e tecnologie sanitarie) al contrario del centro americano che ne prevede solo una. Sulle misure indirette il SCVMC necessita di un supporto esterno minore (circa metà) rispetto ad OSMA. Infine vista la maggiore grandezza del SCVMC rispetto ad OSMA, il costo di retrofitting totale è minore nella struttura fiorentina rispetto a quella californiana.

Conclusioni

Lo studio ha progettato un adeguato strumento di supporto ai decisori per la mitigazione del rischio sismico nelle strutture sanitarie moderne (Stati Uniti e Europa), fornendo un prototipo software in grado di simulare gli effetti ed i costi dell'applicazione delle differenti azioni di retrofitting sismico sulle strutture sanitarie. Inoltre, l'utilizzo di indici quantitativi per la valutazione delle funzioni strategiche e di accoglienza (HTC, IS, HTCI e HPI) permettono analisi approfondite su diversi aspetti dell'ospedale e aiutano il confronto con altre strutture sanitarie, anche se situate in contesti simici differenti.

Zusammenfassung (DE)

Zielsetzung

Krankenhausinfrastrukturen und deren Funktionalität stellen die letzte – und damit die wichtigste – Einheit der medizinischen Antwort nach einem Erdbeben dar. Um einen solchen Notfall angemessen medizinisch koordinieren zu können, ist es grundsätzlich nötig, eine einfache, schnelle und zuverlässigen Risiko-Beurteilung auszuführen, die die Einstufung der direkten und indirekten seismischen Auswirkungen auf alle Akteure im Gesundheitswesen zum Ziel hat. Der Zweck meiner Arbeit ist es, ein Modell zu entwerfen, das die Entscheidungsträger dabei unterstützt, die Auswirkung en von Erdbeben auf das Gesundheitswesen durch die Anwendung von adäquaten Risiko-Reduktions-Strategien zu mindern.

Grundlegende Resultate

Auf einer Kombination zweier Untersuchungsansätze aufbauend wurde eine neue, integrative Methode entwickelt, die mögliche Gefahren adäquat zu identifizieren versucht: Die Theorie komplexer Analysesysteme vergleicht Leontiefs In-Out-Analyse mit der Fehlerbaumanalyse, sowie mit der Abschätzung seismischer Gefährdung mittels Verwendung von speziellen Evaluationsbögen zur raschen Datengewinnung. Erstens beinhaltet das Arbeitsprogramm eine Risiko-Bewertung für Krankenhaussicherheit des OSMA- Krankenhauses in Florenz inklusive dessen Aufnahmekapazität im Notfall. Zweitens wurde die Validität des Modells anhand eines realen Vorfalls (L'Aquila, 2009) getestet. Drittens umfasst es die Risiko - Reduktions - Strukturen des Santa Clara Valley Medical Center in USA. Die theoretische Anwen dung des Modells konnte herausfinden, dass das Leontief-Modell weniger zuverlässig und überzeugend ist als die Fehlerbaumanalyse, besonders in Fällen, in denen eine hohe seismische Aktivität zu verzeichnen ist. Die Risiko- Reduktions- Phase zeigte, dass strukturelle Interventionen keine weitere positive Verbesserung im Vergleich zu nicht-strukturellen Interventionen bieten. Darüber hinaus kann das Florenz Krankenhaus im Notfall nur dann mit einer angemessenen Aufnahmekapazität dienen, wenn simultan eine Maßnahme in zwei Schritten erfolgt, die Reparatur grundlegender technischer Installationen und der in medizinischen Geräte.

Zusammenfassung und Ausblick

Die Studie liefert einen Software-Prototypen zur angemessenen Unterstützung der Entscheidungsträger moderner Gesundheitsinfrastruktur indem er den Typ der Intervention, die technische Komplexität und die wirtschaftlichen Kosten simulieren kann. Weiterhin beinhaltet der neue Ansatz sowohl Strategie- als auch Beherbergungsfunktionen des Gesundheitswesens, indem er quantitative Indizes nutzt, wie z.B. Krankenhaus-Behandlungs-Kapazität durch den “Hospital Treatment Capacity” HTC sowie den Index “Intrinsic Security” (IS), der die Sicherheit der schwächsten Patienten bestimmt und es ermöglicht, verschiedene Krankenhäuser in diversen seismischen Gebieten zu vergleich.

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Glossary

In the field of risk, although several different disciplines work on natural hazards and the impact on a general system, there are many approaches which, according to the different scientific focuses, build and use specific definitions or give different meaning to the same terms. Hence, the following definitions are given with the aim to provide a precise meaning to each specific and general risk related term used within this thesis. Working definitions on the used indices in the work are reported below as well. Besides the definitions within the International PhD program on "Mitigation of risk due to natural hazards on structures and infrastructures ", a part of this glossary is adapted from the European Commission's Framework Program 7 project "MOVE - Methods for the Improvement of Vulnerability Assessment in Europe" which has been updated, integrated and specialized to the specific topic of the thesis: the seismic risk mitigation of health structures.

Severity

The potential consequences of an accident/natural disaster (e.g. earthquake) on the hospital infrastructure resulting in loss of operational performance or occupants safety and security levels degradation.

Occurrence

The probability that a specific event can occur.

Hazard[a]

A potentially adverse physical event, phenomenon or human activity that may cause harm to the predefined System.

Resilience[c]

Adaptive ability of a socio-ecological system to cope and absorb negative impacts as result of the capacity to anticipate, respond and recover from damaging events.

Preparedness[c]

Measures taken to organize and facilitate operations of early warnings, search and rescue activities and rehabilitation of the population and the economy in case of a disaster.

Exposure[c]

The social and material context represented by persons, resources, infrastructure, production, goods, services and ecosystems that may be affected by a hazard. Exposure varies in time and space.

Damage[a]

Describes the physical, biological or chemical effect on an element at risk caused by the impact of a hazard of a given intensity. Damage captures the material harm and is not expressed in monetary terms.

System[a]

The object of investigation for which all sources of hazard are identified and risk analysis is being performed. The system can be composed by a single building or infrastructure element, a suburb of a city, a whole urban region or even an entire country.

Complex system[b]

A complex system is a system composed of interconnected parts that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts.

Vulnerability[c]

The susceptibility to suffer damages or the intrinsic fragility of exposed elements, systems or communities that favours loss when affected by hazard events.

Capacity[c]

A combination of all strengths and resources available within a community, system or organisation that can reduce the level of risk, or the effects of a disaster.

Capacity to anticipate[c]

Ordered and coherent set of strategies, programs and projects that orient activities favouring the reduction, prevision and control of risk and emergency preparedness and post impact disaster recovery. This includes all the retrofitting actions to be carried out for improving seismic behavior of the system.

Capacity to cope[c]

The ability of people, organizations, systems and/or communities, using available skills and resources to face and manage adverse conditions, emergencies or disasters that could lead to or are caused by a hazard or harmful process.

Capacity to recover[c]

Capacity to restore adequate and sustainable living conditions in an area or community affected by a disaster. This may be achieved by means of rehabilitation, repair, reconstruction or replacement of destroyed, interrupted or deteriorated infrastructure, goods and services.

Vulnerability assessment[c]

The measurement of vulnerability related to the degree of exposure, susceptibility and lack of resilience of a general system.

Risk[c]

The potential occurrence of harmful consequences or losses resulting from interactions between natural or anthropogenic hazards and vulnerable conditions.

$Risk = Vulnerability \times Hazard$

Element-at-Risk (EaR)[a]

A single or a group of persons or objects within the predefined System that are susceptible and exposed to the impact of a Hazard. In order to guarantee a complete coverage, all Element at Risk collectively should compose the entire System that is being investigated.

Risk assessment[c]

The process of apprehending the nature of risk and determining its level. It combines the evaluation by experts and the evaluation by stakeholders.

Risk analysis[c]

Evaluation of a risk by experts which is based on hazard and vulnerability assessment, and is performed on scientific bases.

Risk management[a]

The systematic application of management policies, procedures and practices to the tasks of a multidisciplinary process leading to the planning and application of policies, strategies, to the task of identifying, assessing, treating, communicating, reviewing and monitoring Risk.

Risk mitigation[a]

The planning and execution of measures designed to reduce risk to acceptable levels.

Direct intervention

All those seismic retrofitting actions carried out by directly intervening on the system such as the structural or non-structural activities.

Indirect intervention

All those seismic retrofitting actions carried out by indirectly intervening on the system such as the usage of medical mobile units or the medical evacuation to other hospitals.

Hospital Treatment Capacity

The number of surgical operations feasible per hour by the hospital.

Hospital Treatment Demand

The number of people that requires surgical treatment.

Hospital Treatment Capacity Index

The estimation of the treatment capacity level of the hospital to comply with the local medical needs.

Intrinsic Security

The capacity of the health structure to guarantee safe and secure hospital beds including the ones in the Intensive Care Unit.

Hospital Performance Index

Numerical combination between the strategic (HTCI) and the hosting (IS) functions of the hospital system according to the hospital category: city, country or small town hospital.

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[a]Pliefke T., Sperbeck S. and Urban M. The probabilistic risk management chain - general concept and definitions

[b]Joslyn, C. and Rocha, L. (2000). Towards semiotic agent-based models of socio-technical organizations, Proc. AI, Simulation and Planning in High Autonomy Systems (AIS 2000) Conference, Tucson, Arizona, pp. 70-79.

[c]European Commission's Framework Program 7 project "MOVE - Methods for the Improvement of Vulnerability Assessment in Europe

Introduction

As it constitutes the final point in the rescue chain, the hospital system is one of the most important elements of medical responses to the aftermath of earthquakes. The operational continuity of health structures is essential to the efficient response of the emergency medical system just as it is necessary to guarantee a very high level of building resistance to protect medical patients during an earthquake who are likely not self-sufficient or depending on life-support devices. Although many structural and non-structural actions already exist in the field of seismic reduction, their application remains difficult given the degree of complexity of hospital systems.

Hence, the aim of this thesis is to provide healthcare decision makers with a "decision support system (DSS)" so to appropriately plan retrofitting interventions in order to reduce seismic risk in hospitals.

This thesis is divided into two main parts. The first part reports upon the development of the model and the second uses case studies to demonstrate its application.

The first part starts in chapter 1 with a general overview on the risk management process, paying considerable attention to its application to health care and describes the international state of the art in the field of hospitals and seismic risk and it explains the role of the hospital within the entire rescue chain during earthquakes. Chapters 2-4 present the developed methodology for the hospital risk mitigation according to three specific phases: vulnerability assessment, risk analysis and risk mitigation.

The second part of the thesis starts with the application of the integrated model, based on a combination of the complex systems theory and the rapid seismic assessment, at OSMA Hospital in Florence (chapter 5). This is followed by the validation with the application to the real case given by the San Salvatore hospital during the 2009 earthquake (chapter 6). In chapter 7 the same model is applied to the US hospital Santa Clara Valley Medical Center (SCVMC). The model application included accessing hospital data about structural, technology and organizational features and conducting interviews with hospital engineers and medical doctors. The use of examples from the United States and Europe gives a general model, feasible to every modern general hospital. Proper quantitative indices were also defined with the aim of objectively estimating the performance level of the hospital and carrying out hospital benchmarking in risk analysis.

Discussions and case study comparisons are reported in chapter 8 by considering both scenarios with the application of direct and indirect interventions. A cost analysis according to the different mitigating actions is reported as well.

Finally, chapter 9 reports on the prototypization of the DSS by the use of the standard software mock up and prototype models in the information technology area before the conclusions and further developments.

Part I.

METHODOLOGY

1. Seismic Risk Management in Hospitals

1.1. Overview

1.1.1. *The medical response: a system within a complex system*

According to Quarentelly (1985) disaster is defined as a crisis situation that far exceeds the capabilities. Despite of the definition, which states that cannot be a perfect ideal system that prevents damage, because then it would not be a disaster, currently, disasters can be reasonably and in some cases accurately predicted or mitigated by technological, social and scientific advances[1]. As reported in figure 1.1, the trend of disaster occurrence in the world from the 1950 to 2011 has been continuously increasing [2]. Especially regarding the seismic events, they have been striking constantly during the last 60 years, 5 big events just in the last four years (L'Aquila - Italy 2009, Padang - Indonesia 2009, Chile 2010, Haiti 2010, Christchurch - New Zealand 2011).

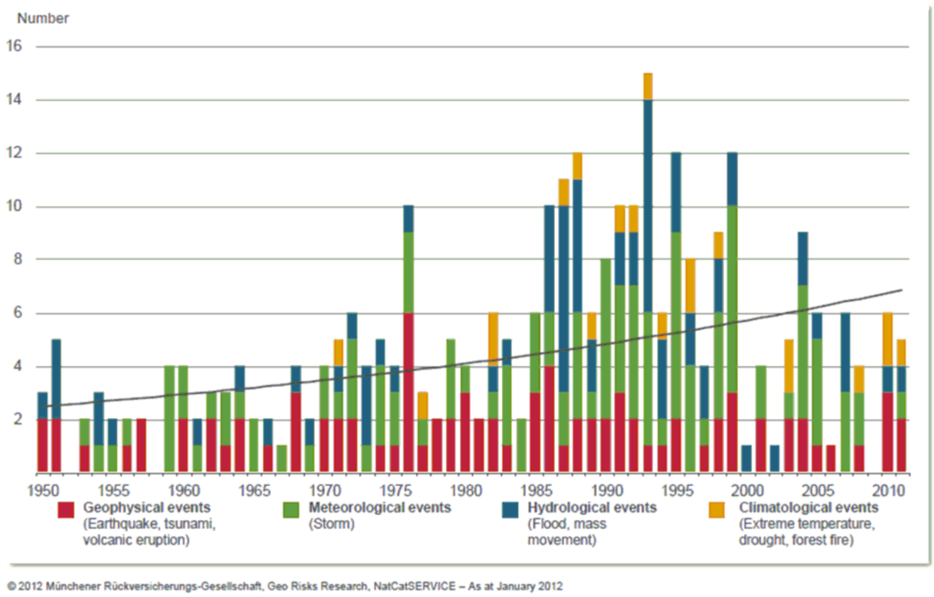

Figure 1.1.: Great natural catastrophes worldwide 1950-2011: number of events with trend [2].

During earthquakes, the medical response chain depends on many different and complex interconnected systems which are: the hospital infrastructure, the road viability, the rescue and search and all those civil protection activities regarding the security, technical support, aerial medical evacuation and field hospital installation. Every single system of the chain depends on the others and is directly responsible for the others' performance. According to the Italian legislature, the first act providing guidelines and suggestions on the medical response during disasters is the Law n. 225 (February 24th, 1992) [3] which formally founded the Italian Civil Protection by defining which specific activities are under the responsibility of which specific institutions (municipalities, central government, fire brigades, police and medical emergency offices). The specific activities depend on the phase where they belong to, which are the followings: “coordination phase”, ”prevention, rescue and search and recover” and “disaster types definitions”. The last phase defines the domain of intervention of the civil protection components in relation to the disaster types:

- Natural or man made events potentially solvable by the single local administration (municipal level);
- Natural or man made events potentially solvable by the synergy of multiple local administrations (regional or provincial level);
- Natural or man made events potentially solvable by extraordinary powers and activities (National level).

The necessity of organizing an appropriate medical response in case of disasters if foreseen only for the last type of events. The organizational process includes planning and prevention and includes the emergency ambulance department and the hospital system, classified under the term Health National System. Next, with the provision of the legislative act n. 112 (march 31st 1998) [4] some of the central activities are transferred under the regional level, and with the publication of the Internal Affair Minister Act DPCM 13/02/2001 [5], a practical guideline is finally given in order to standardize the planning activity concerning the medical res ponse management during disasters. The suggested steps include:

- Local risk identification;
- Risk analysis;
- Scenario development;
- Disaster planning publication.

As reported in figure 1.2(a), when the acute emergency phase is solved within the 12 hours, the disaster medical response chain indicates the use of only regular hospitals, while in case of emergency duration over the 12 hours limit, the medical chain foresees the integrated use of regular and field hospital units, see figure 1.2(b). Most of the times, the use of mobile medical units aims to provide a first clinical stabilization in order to guarantee a safe transportation to hospitals, especially for the severe injured people. For this reason a triage process is always recommended at the event site as well as beside the hospital emergency department for both scenarios (a) and (b). With the term triage is intended the process of determining the priority of patients' treatments based on the severity of their condition [6] The term comes from the French verb trier, meaning to separate, sift or select [7]. Triage may result in determining the order and priority of emergency treatment, the order and priority of emergency transport, or the destination for the patient. Triage is fundamental for the medical response during disasters (e.g. earthquake) because, given the high number of casualties, a good triage can optimize the use of the limited resources for treating only the most severe injured people and resulting very important in saving lives[9].

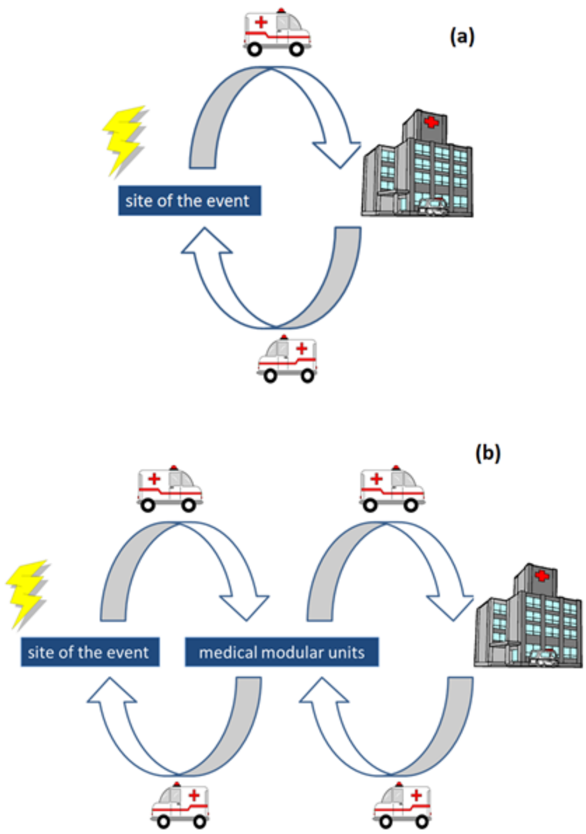

Figure 1.2.: Medical response chain according to the different

One of the most used triage model in the international context is the S.T.A.R.T. system (Simple Triage and Rapid Treatment), developed by the California emergency workers for use in earthquakes at Hoag Hospital in Newport Beach, California. START triage separates the injured into four groups:

- The expectant who are beyond help – blue tag;

- The injured who can be helped by immediate transportation – red tag;
- The injured whose transport can be delayed – yellow tag;
- Those with minor injuries, who need help less urgently – green tag.

The START model, which introduces the blue tag for those casualties who can't be saved with the limited medical resources during the disaster, is based on three simple clinical evaluations which are the respiratory frequency, the pulse rate and the mental status, see the flowchart in figure 1.3. It is now clear by the analysis of the medical response chain during disasters how the hospital system represents, for any type of event, the final point of the whole medical response. For this reason in the next sections the focus will be given to the development of a risk management process for hospital in case of earthquakes.

Figure 1.3.: S.T.A.R.T. triage flow chart for the casualty tagging [8].

1.1.2. *Hospital system*

A proper seismic risk management process in hospitals should consider the seismic scenario where the “hospital system” is exposed to the event in order to find out which may be the most critical affected elements and how they could be strengthened. Hospital system must face immediately with a huge number of casualties. The hospital scenario during disasters and especially in aftermath of earthquakes sees hospitals facing a huge number of casualties which mostly reach the structure within the first 24 hours. Indeed by investigating the number of survivors' distribution over time after an earthquake, the “golden 24 hours” should be considered as a measurement of the predicted probability of finding survivors over time after an earthquake [10-12]. The earthquake epidemiologic distribution shows that after 24 hours, 80% of the extracted victims are still alive, afterwards the survival rate decreases rapidly [13].

Hospital resources are limited with respect to the medical needs.

Three different “casualties waves” reach the emergency department in aftermath of an earthquake. First wave is the biggest and it is composed by the green triaged casualties which get the hospital by themselves by using public transports and/or own cars without necessarily passing through a triage control at the site of the event, see figure 1.4 [44]. Second wave is composed by the red and yellow tagged casualties which are ambulance transported. Finally the third wave includes casualties' relatives and friends with the need of psychological support and mass media. Clinically is really important to have a specific triage station supporting the hospital emergency department with a filtering role to the health structures in order to minimize the use of the limited medical resources with the least severe casualties.

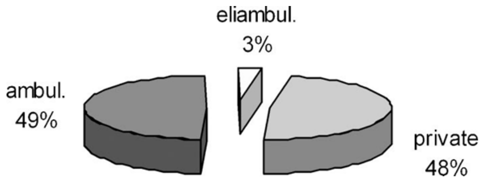

Figure 1.4.: Casualties transportation to hospitals [44]

Hospital can't be functional During earthquakes the hospital can be damaged and losing a partial or the whole treatment capacity. Table 1.1 reports the health facilities' performance degradation due to the resulting damages during the Bam earthquake [14]. Fourteen facilities got 100% damage while the remaining two hospitals (Emam District Hospital and Mahdieh Maternity Hospital) resulting 50% damaged. While the management of the hospital overcrowding scenario can be organized by a proper emergency planning, the problem presented here needs a deeper analysis which should consider the health structure vulnerability, the level of medical needs satisfaction (before and after the event) and how this levels according to the specific hospital can be improved. For this reason, in the next paragraphs a systematic review on the international state of art of risk management is carried out by focusing on the specific applications to hospitals.

Health Facility	Number of beds	Percent Damage
Health House Urban	95	100
Rural Health Center(RHC)	14	100
Health Center(UHC)	10	100
Health Posts (Urban)	5	100
Maternity Facilities(as part of RHC)	5	100
Emam District Hospital (public)	136	50
Mahdieh Maternity Hospital (public)	54	40
Aflatoonyan Hospital (private)	6	100
Emergency Station(115)	1	100
Behvarz Training Center	1	100
District Health Network Expansion Center	1	100
District Health Care Management Center	1	100
Faculty of Nursing and Paramedics	2000miles	100
Dormitory of the Faculty of Nursing	1500miles	100

Table 1.1.: District Health Care Delivery System and the damage due to the earthquake in Bam[14].

1.2. Analysis of the State of Art

According to the following definition, risk management is the identification, assessment, and prioritization of risks followed by coordinated and economical application of resources to minimize, monitor, and control the probability and/or impact of unfortunate events or to maximize the realization of opportunities[14]. Although risk management is a continuous activity, the effects of an appropriate risk management process are very evident during disasters (i.e. natural or man-made). Risk should be first defined, in order to be reduced since it strongly depends on the context where the object of study is located (i.e. financial-risk, environmental-risk, technical-risk, health-risk, social-risk). A unique definition of risk cannot always be applied. In Pliefke et.al. [a] there are several definitions of risk regarding disasters, and in spite of the fact that the context of the object of study may vary, defining the risk should always include the definitions of the following elements: hazard, loss, damage, vulnerability, exposure and consequences. Next, the state of art or risk management is analyzed, in order to see how the international regulations and scientific literature define and contextualize general and specific risks, especially the ones concerning healthcare and hospital infrastructure.

1.2.1. ISO Standards

1.2.1.1. General

This International Organization for Standardization (ISO) provides technical guidelines in many social and industrial sectors. In the case of the ISO 31000:2009 and ISO 31010:2009, they concern principles and generic guidelines on risk management since all activities of an organization involve risks [16, 17] and represents the base for every risk management activity application to any area of interest while the ISO Guide 73:2009 provides the definitions of generic terms related to risk management [18]. The Risk management process should ensure that organizations have an appropriate response to the hazards or ordinary damages affecting them. Risk management should thus help avoid ineffective and inefficient responses to risk that can prevent legitimate activities and/or distort resource allocation. To be effective within an organization, risk management should be an integrated part of the organization's overall governance, management, reporting processes, policies, philosophy and culture. The same risk management approach can be adopted to all activities of an organization including projects, defined functions, assets, and products or activities and will in turn strengthen the linkages between these activities and the organization's overall objectives. The relationship between the principles for managing risk, the risk management framework and the risk management process is shown in Figure 1.5.

To be successful, the risk management should be part of a general risk management framework within the organization which gives, according to the internal organizations and the general context, the operational resources and tools for carrying out the risk management activities, see figure 1.6.

Moreover, the framework should ensure that all the risk information derived from the process must be adequately reported and used as a basis for future updates, decision making and accountability. As reported in figure 1.7, the risk management process includes five activities: communication and consultation, establishing the context, risk assessment, risk treatment, monitoring and review.

1.2.1.2. Communication and consultation

In order to fully understand the risk connection with the context, communication and consultation with internal and external stakeholders should take place at each stage of the risk management process and addressing issues relating to the risk itself, its consequences (if known), and the measures being taken to manage it such as:

- help define the context appropriately;
- ensure that the interests of stakeholders are understood and considered;

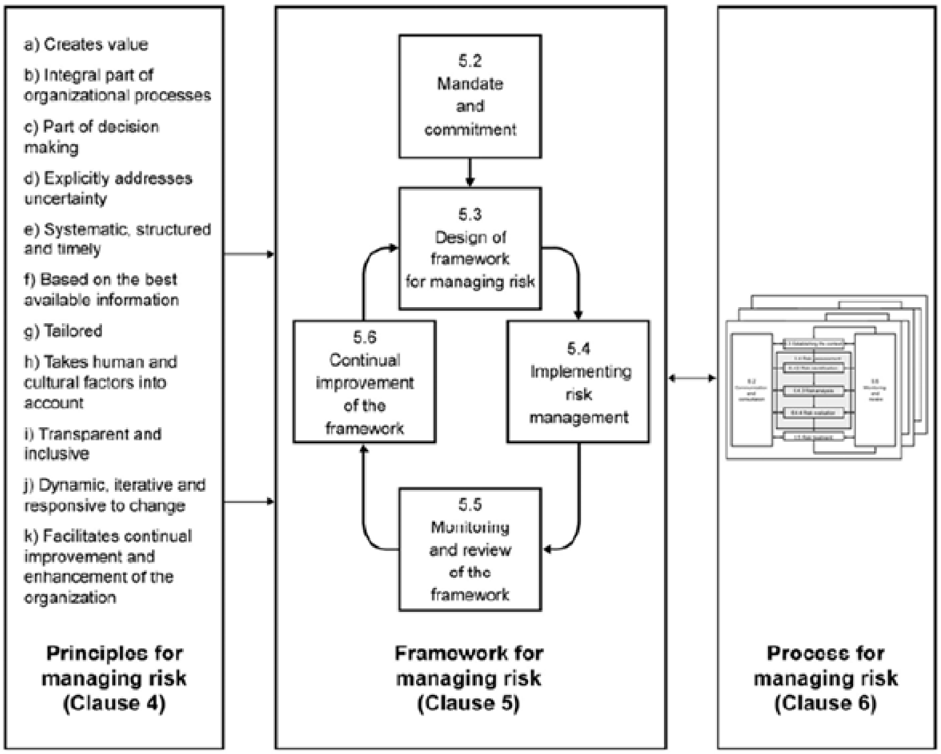

Figure 1.5.: ISO 31000:2009 - Risk Management - Principles and guidelines on implementation.

- bring different areas of expertise together for analyzing risks;
- help ensure that risks are adequately identified;
- ensure that different views are appropriately considered in evaluating risks;
- enhance appropriate change management during the risk management process;
- secure endorsement and support for a treatment plan;
- develop an appropriate internal and external communication and consultation plan.

1.2.1.3. Establishing the context

By establishing the context, the internal and external parameters can be defined when managing risk. The external context means the external environment in which the organization seeks to achieve its objectives and can include, but it is not limited to the cultural, political, legal, regulatory, financial, technological, economic, natural and environmental, whether international, national, regional or local key drivers,

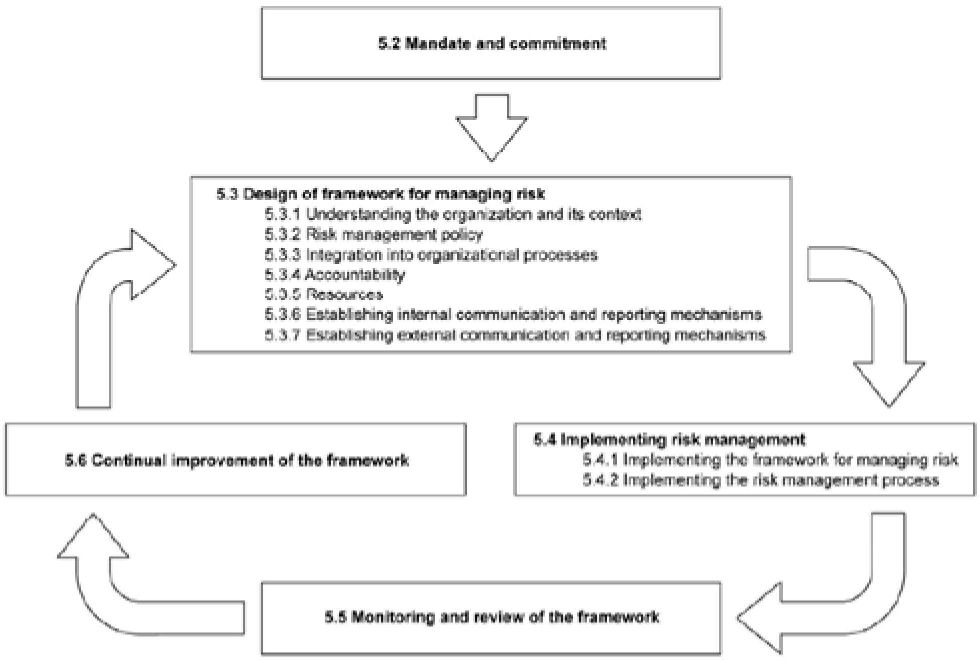

Figure 1.6.: ISO 31000:2009 –General Risk Management Framework.

and trends having impact on the objectives of the organization and perceptions and values of external stakeholders.

For internal context, it is considered the internal environment in which the organization seeks to achieve its objectives. Internal context is anything within the organization that can influence the way in which an organization will manage risk, and it should be established because:

- risk management takes place in the context of the objectives of the organization;
- objectives and criteria of a particular project or activity should be considered in the light of objectives of the organization as a whole;
- a major risk for some organizations is failure to achieve their strategic, project or business objectives, and this risk affects ongoing organizational commitment, credibility, trust and value.

It is necessary to understand the internal context regarding:

- capabilities, understood in terms of resources and knowledge;
- information systems, information flows, and decision making processes;
- internal stakeholders;
- policies, objectives, and the strategies that are in place to achieve them;
- perceptions, values and culture;

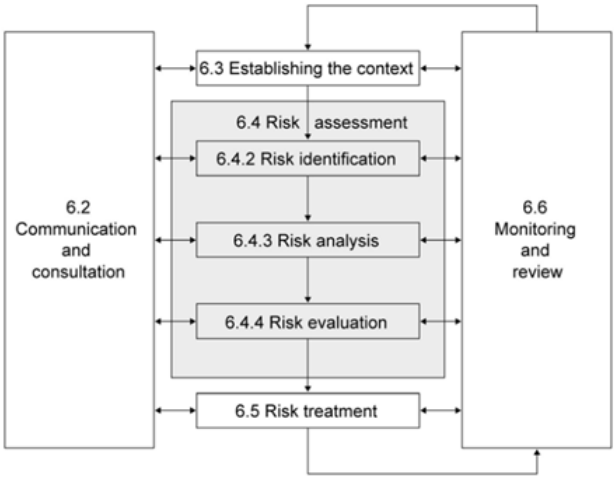

Figure 1.7.: ISO 31000:2009 –Activities involved during the Risk Management Process.

- standards and reference models adopted by the organization;
- structures (e.g. governance, roles and accountabilities).

1.2.1.4. Risk assessment

Risk assessment is the overall process of risk identification, risk analysis and risk evaluation.

Risk identification

The organization should identify sources of risk, areas of impacts, events and their causes and their potential consequences. The aim of this step is to generate a comprehensive list of risks based on those events that might enhance, prevent, degrade or delay the achievement of the objectives.

What can happen, where and when?

The aim is to generate a comprehensive list of sources of risks and events that might have an impact on the achievement of each of the objectives identified in the context. These events might prevent, degrade, delay or enhance the achievement of those objectives. These are then considered in more detail to identify what can happen.

Why and how it can happen?

Having identified what might happen, it is necessary to consider possible causes and scenarios. There are many ways an event can occur. It is important that no significant causes are omitted.

Tools and techniques

Approaches used to identify risks include checklists, judgments based on experience and records, flow charts, brainstorming, systems analysis, scenario analysis and systems engineering techniques. The approach used will depend on the nature of the activities under review, types of risk, the organizational context and the purpose of the risk management study.

Risk analysis

Risk analysis is about developing an understanding of the risk. It includes an input to decisions on whether risks need to be treated and the most appropriate and cost-effective risk treatment strategies. Risk analysis involves consideration of the sources of risk, their positive and negative consequences and the likelihood that those consequences may occur. Factors that affect consequences and likelihood may be identified. Risk is analyzed by combining consequences and their likelihood. In most circumstances existing controls are taken into account. A preliminary analysis can be carried out so that similar risks are combined or low-impact risks are excluded from detailed study. Excluded risks should, where possible, be listed to demonstrate the completeness of the risk analysis.

Evaluate existing controls

Identify the existing processes, devices or practices that act to minimize negative risks or enhance positive risks and assess their strengths and weaknesses. Controls may arise as outcomes of previous risk treatment activities.

Consequences and likelihood The most pertinent information sources and techniques should be used when analyzing consequences and likelihood. Sources of information may include the following:

- Past records;
- Practice and relevant experience;
- Relevant published literature;
- Market research;
- The results of public consultation;
- Experiments and prototypes;
- Economic, engineering or other models;
- Specialist and expert opinions.

While regarding with the tools and techniques, they include:

- structured interviews with experts in the area of interest;
- use of multi-disciplinary groups of experts;
- individual evaluations using questionnaires;

- use of models and simulations.

Furthermore, in the part called “Types of Analysis” the norm reports the different risk analysis which can be undertaken to varying degrees of detail depending upon the risk, the purpose of the analysis, and the information, data and resources available. Analysis may be qualitative, semi-quantitative or quantitative or a combination of these, depending on the circumstances. Moreover, the ISO 31000 underlines the necessity to control and evaluate the data certainty that is called “Sensitivity analysis.” Since some of the estimates made in risk analysis are imprecise, a sensitivity analysis should be carried out to test the effect of uncertainty in assumptions and data. Sensitivity analysis is also a way of testing the appropriateness and effectiveness of potential controls and risk treatment options.

Risk evaluation

The purpose of risk evaluation is to assist in making decisions, based on the outcomes of risk analysis, about which risks need treatment to prioritize treatment implementation. Risk evaluation involves comparing the level of risk found during the analysis process with risk criteria established when the context was considered. The risk evaluation can also lead to a decision not to treat the risk in any way other than maintaining existing risk controls.

1.2.1.5. Risk treatment

Risk treatment involves selecting one or more options for modifying risks, and implementing those options. Risk treatment involves a cyclical process of assessing a risk treatment; deciding whether residual risk levels are tolerable or not; if not tolerable generating a new risk treatment; and assessing the effect of that treatment until the residual risk reached complies with the organization’s risk criteria. Risk treatment options are not necessarily mutually exclusive or appropriate in all circumstances. The options can include the following:

- avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk;
- seeking an opportunity by deciding to start or continue with an activity likely to create or enhance the risk;
- removing the source of the risk;
- changing the nature and magnitude of likelihood;
- changing the consequences;
- sharing the risk with another party or parties;
- retaining the risk by choice.

Selecting the most appropriate risk treatment option involves balancing the costs and efforts of implementation against the benefits derived having regard to legal, regulatory, and other requirements, social responsibility and the protection of the natural environment. Decisions should also take into account risks that can warrant risk treatment actions that are not justifiable on economic grounds e.g. severe (high negative consequence) but rare (low likelihood) risks. The organization can benefit from the adoption of a combination of treatment options. Where risk treatment options can impact on risk elsewhere in the organization, these areas should be involved in the decision. Though equally effective, some risk treatments can be more acceptable to stakeholders than others. Risk treatment itself can introduce risks. A significant risk can be the failure or ineffectiveness of the risk treatment measures. The residual risk should be documented and subjected to monitoring, review and, where appropriate, further treatment.

1.2.1.6. Monitoring and review

Monitoring and review should be a planned part of the risk management process. Responsibilities for monitoring and review should be clearly defined. The organization's monitoring and review processes should encompass all aspects of the risk management process for the purposes of:

- analyzing and learning lessons from events, changes and trends;
- detecting changes in the external and internal context including changes to the risk itself which can require revision of risk treatments and priorities;
- ensuring that the risk control and treatment measures are effective in both design and operation; and identifying emerging risks.

Actual progress in implementing risk treatment plans provides a performance measure and can be incorporated into the organization's performance management, measurement and internal and external reporting activities. Monitoring and review can involve regular checking or surveillance of what is already present or can be periodic or ad hoc. Both aspects should be planned. The results of monitoring and review should be recorded and internally or externally reported as appropriate and should also be used as an input to the review of the risk management framework. Regarding the possible types of assessment techniques, ISO 31010:2009 reports a classification based on the relevance of influencing factors (low, medium and high) and on possibility to have quantitative outputs, see table 1.2.

Type of risk assessment technique	Description	Relevance of influencing factors			Can provide Quantitative output
		Resources and capability	Nature and degree of uncertainty	Complexity	
Scenario analysis	Possible future scenarios are identified through imagination or extrapolation from the present and different risks considered assuming each of these scenarios might occur. This can be done formally or informally qualitatively or quantitatively	Medium	High	Medium	No
Toxicological risk assessment	Hazards are identified and analysed and possible pathways by which a specified target might be exposed to the hazard are identified. Information on the level of exposure and the nature of harm caused by a given level of exposure are combined to give a measure of the probability that the specified harm will occur	High	High	Medium	Yes
Business impact analysis	Provides an analysis of how key disruption risks could affect an organization's operations and identifies and quantifies the capabilities that would be required to manage it	Medium	Medium	Medium	No
Fault tree analysis	A technique which starts with the undesired event (top event) and determines all the ways in which it could occur. These are displayed graphically in a logical tree diagram. Once the fault tree has been developed, consideration should be given to ways of reducing or eliminating potential causes / sources	High	High	Medium	Yes
Event tree analysis	Using inductive reasoning to translate probabilities of different initiating events into possible outcomes	Medium	Medium	Medium	Yes
Cause/ consequence analysis	A combination of fault and event tree analysis that allows inclusion of time delays. Both causes and consequences of an initiating event are considered	High	Medium	High	Yes
Cause-and-effect analysis	An effect can have a number of contributory factors which may be grouped into different categories. Contributory factors are identified often through brainstorming and displayed in a tree structure or fishbone diagram	Low	Low	Medium	No

Table 1.2.: Example of risk assessment techniques [17].

1.2.2. International Guidelines in Healthcare

1.2.2.1. JCAHO Standard EC.1.4

The Joint Commission on Accreditation of Healthcare Organizations (JCAHO) is a United States-based nonprofit organization that accredits more than 19,000 health care organizations and programs in the United States[19, 20]. The Intent of EC.1.4 is to provide a tool for completing a security management plan which describes how the organization will establish and maintain a security management program to protect staff, patients, and visitors from harm during disasters and in ordinary activity. The new emergency management standards for hospitals, long term care, behavioral health, and ambulatory care implemented on January 1, 2001 introduces concepts into existing standards and infuses the concept of community involvement into the management process and assists health organizations in preparing for, and managing, a variety of potential emergencies such as earthquakes. The plan addresses four phases of emergency management: mitigation, preparedness, response, and recovery. At a minimum, the emergency management plan is developed with the involvement of the hospital leaders, including those of the medical staff. The Joint Commission on Accreditation of Healthcare Organizations (JCAHO) has significantly revised the standard for emergency management (EC.1.4) in the 2001 edition of the Comprehensive Accreditation Manual for Hospitals. The hospital must now function as an integrated entity within the scope of the broader community. Although hospitals have always had to respond to a variety of disasters, the 2001 standard continues to state that the hospital response plans must be based on a hazard vulnerability analysis performed by the hospital. Although the terminology "hazard vulnerability analysis" may be new to many hospitals, the concept itself is not new. The approach reported in the document includes the following main points:

- Risk Analysis
  - Hazard Analysis;
  - Probability evaluation;
  - Severity analysis;
  - Preparedness evaluation.
- Analysis tool implementation.

Hazard vulnerability analysis is often based on an all hazards approach. This means that one begins with a list of all possible disasters, regardless of their likelihood, geographic impact, or potential outcome. The list may be the result of a committee brainstorming session, research, or other methodology, and should be as comprehensive as possible. It may be helpful to divide the potential hazards into categories to focus the thought process. Typical categories may include natural hazards, technological hazards, and human events. Ultimately, each identified hazard will be evaluated for its probability of occurrence, risk to the organization, and the organizations current level of preparedness. Establishing the probability of occurrence of these various events is only part objective and statistical, the remainder can best be considered intuitive or highly subjective. Each hazard should be evaluated in some terms that will reflect its likelihood, for example, by using the qualitative terms of high, medium, low, or no probability of occurrence. For Severity is intended the potential impact that any given hazard may have on the organization. It must be analyzed to include a variety of factors, which may include, but are not limited to the following:

- Threat to human life;
- Threat to health and safety;
- Property damage;
- Systems failure;
- Economic loss;
- Loss of community trust/goodwill;
- Legal ramifications.

The threat to human life and the lesser threat to health and safety are considered to be so significant that they are given separate consideration on the hazard vulnerability analysis document. The remaining three categories on the analysis tool classify risk factors as to their disruption to the organization in high, moderate, or low classification. From the bulleted list above, property damage, systems failure, economic loss, loss of community trust, and legal ramifications are all considered together to determine the level of risk. Seismic activity may virtually destroy a building, or render it uninhabitable. In the most severe scenario of this type, the property damage will also include equipment and supplies within the facility. Systems failure may have been the cause of the emergency in the first place. A major utility failure may require backup equipment or service that is significantly less convenient, or may not be sustainable for a lengthy time. Even though an alternate system is available, the failure will typically cause a hospital to implement emergency plans. A related issue to loss of goodwill is the potential for legal ramifications in the aftermath of a disaster. If errors were made in the management of the emergency, if lives were lost or injuries occurred, the hospital could face legal action. The evaluation of the level of preparedness to manage any given disaster has to consider organizational procedures, standards following and resources availability to support the hospital in its response. The hazard vulnerability analysis tool has to evaluate the organization's preparedness level as good, fair, or poor. An alternative way of approaching this issue is to evaluate each hazard based on the amount of improvement needed, for example, slight, moderate, or major. Below (figure 1.8) is reported an example of check list for vulnerability evaluation and collect the information suggested by the American Society for Healthcare Engineering ASHE [20,45].

1.2.2.2. World Health Organization (WHO) and United Nations (UN) Guidelines

PAHO/WHO - Disaster Mitigation Program

In the year 2000, the Pan American Health Organization/World Health Organization International Hospital Mitigation Advisory Committee, through a multidisciplinary approach, published within the Disaster Mitigation in Health Facilities series, the following four guidelines aiming to different aspects of the common goal: disaster mitigation in hospitals. The four books, including General, Administrative, Architectural and the Engineering Issues, aim to examine the potential problems that can arise when disasters strike health facilities, and offering specific mitigation measures on the key components for providing continuously the vital services during and in the immediate aftermath of a major emergency such as seismic events, which represent the natural disaster that mostly affects the health facilities [21].

United Nations (UN) - Disaster Risk Management Program

During the year 2007, the Indian National Disaster Management Division within the Disaster Risk Management Program produced a specific guideline on the "Seismic Safety of Non-Structural Elements & Contents of Hospital Buildings".

The high attention to non-structural elements depends on the following factors [22]:

- Hospital facilities must remain as intact as possible by providing routine medical services as well as attending to the possible increase in demand for medical treatment following an earthquake;
- In contrast to other types of buildings, hospitals accommodate a large number of patients who, due to their disabilities, are unable to evacuate a building in the event of an earthquake;

- Hospitals have a complex network of electrical, mechanical and sanitary facilities as well as a significant amount of costly equipment all of which are essential both for the routine operation of the hospital and for emergency care. Failure of these installations due to a seismic event cannot be tolerated in hospitals as this could result in its functional collapse;
- The ratio of the cost of nonstructural elements to the total cost of the building is much higher in hospitals than in other buildings. While nonstructural elements represent approximately 60% of the value in housing and office buildings, in hospitals these values range from 80% to 90%, mainly due to the cost of medical equipment and specialized facilities.

In the year 2008, still within the Disaster Risk Management Program, the Disaster Management Unit of the United Nations Development Program of India published guidelines for Hospital Emergencies Preparedness Planning [23].

EVENT	PROBABILITY				RISK					PREPAREDNESS			TOTAL
	HIGH	MEDIUM	LOW	NONE	LIFE THREAT	HEALTH/ SAFETY	HIGH DISRUPTION	MODERATE DISRUPTION	LOW DISRUPTION	POOR	FAIR	GOOD	
SCORE	3	2	1	0	5	4	3	2	1	3	2	1	
NATURAL EVENTS													
Hurricane Winds													
Tornado													
Severe thunderstorm													
Snow fall													
Blizzard													
Ice storm													
Earthquake													
Temperature extremes													
Drought													
Flood, external													
Wild fire													
Landslide													

Figure 1.8.: ASHE check list for the hazard vulnerability evaluation [20].

WHO - Assessment of Health Facilities in Responding to Emergencies

The publication of the protocol "Assessment of Health Facilities in Responding to Emergencies" published by World Health Organization in 2006 is a management tool for health professionals evaluating the preparedness of health facilities for dealing with disasters by providing definitions, evaluation checklists and relevant case studies [24]. The guideline focuses on the preparedness assessment and vulnerability assessment because performing regular vulnerability assessments allows a health facility to effectively identify and modify factors that increase its susceptibility and decrease its resilience [24]. The manual is divided into three main parts: a questionnaire and an overview of the health facility's capabilities, Assessment of General Emergency and Preparedness, Structural Vulnerability - Non-structural Vulnerability -Functional Vulnerability and Assessment of Preparedness for Specific Emergencies which are becoming increasingly relevant: Industrial Emergencies, Infectious Disease Outbreaks, and Biological, Chemical and Radiologic Emergencies. The manual presents a series of evaluation checklists that were formulated based on information from current literature.

WHO - Hospital Safe from Disasters

During the World Conference on Disaster Reduction, held from 18 to 22 January 2005 in Kobe, Hyogo, Japan, the present framework was adopted for starting actions in the period 2005-2015 with the aim to build the resilience of nations and communities to disasters [26]. The conference gave a unique opportunity to promote a strategic and systematic approach to reducing vulnerabilities and risks to hazards especially for the hospital sectors as reported by the following points extracted by the original document:

- Integrate disaster risk reduction planning into the health sector; promote the goal of "hospitals safe from disaster" by ensuring that all new hospitals are built with a level of resilience that strengthens their capacity to remain functional in disaster situations and implement mitigation measures to reinforce existing health facilities, particularly those providing primary health care.
- Protect and strengthen critical public facilities and physical infrastructure, particularly schools, clinics, hospitals, water and power plants, communications and transport lifelines, disaster warning and management centers, and culturally important lands and structures through proper design, retrofitting and re-building, in order to render them adequately resilient to hazards.

In the year 2006, the World Health Organization, Regional Office for Europe published a handbook to provide to decision makers a practical guideline in assessing the vulnerabilities of health facilities by identifying structural and functional gaps and weaknesses [27]. The procedure takes into account the features characteristic of Europe (such as the typical building types used for health facilities), employ existing methods for assessing vulnerability, and use the latest version of the European Macroseismic Scale (EMS-98) for determining possible seismic demand. Three main vulnerability categories are evaluated, structural, nonstructural and administrative/organizational while in the annexes the evaluation forms for the rapid assessment are reported. In the year 2008 the Western Pacific Part of the World Health Organization and the Philippine Department of Health published a manual entitled “Hospital should be safe from disasters” where are listed a set of indicators in order to guide the hospital administrators to make hospitals safe from disaster through the following definition [28]: a safe hospital will not collapse in disasters killing patients and staff, will be able to function and supply critical services in emergencies and will be organized with contingency plans in place and health personnel trained to keep the network operational.

Finally, in the year 2009 the WHO Regional Office for South-East Asia published a special issue volume entitled “World Health Day 2009 – Save lives: make hospital safe in emergencies” where are reported some case studies on hospital vulnerability assessment. The original contribution of the publication is the definition of a Hospital Safety Index (HSI)which quantitatively defines the minimum performance levels and allows benchmarking amongst different health structures [29,30].

In conclusion the risk management in hospitals reported in the international guideline above is limited to the vulnerability assessment since any hazard analysis is deeply carried out. According to the definitions in the glossary, the risk is evaluated as a combination between the vulnerability of the system and the impact of the hazard. Regarding the elements to be considered in the assessment, non-structural components are considered as important as the structural elements and the internal complexity of the system is cited as an important factor but non clearly described (e.g. hospital internal connections) or explained especially for modern hospitals where the functional or technological connections amongst the hospital systems are more numerous, virtual and complicated to be detected. Only one of the guidelines cited above refers to modern hospital vulnerability assessment [27]. In fact, in order to complete the risk management process applied to hospitals, in the next paragraphs the risk management chain will be described and adapted to the hospital case.

1.2.3. The ’Critical Infrastructures’ Analysis

Currently, several models have been developed or modified for being applied to the seismic risk assessment in hospitals. Most of them include models from the critical infrastructure area [31] especially within the complex systems theory such as the reliability analysis [32, 33, 34, 35, 36], the input-output analysis Leontief model [37, 38, 39], from the network flow modeling [a,40] and the dynamic simulation area[41]. With respect to the international WHO/UN guidelines (the check lists and the evaluation forms are reported in the next paragraph), the models belonging to the critical infrastructure analysis area are able to take the complexity of system organization into account but they present some weakness such as they do not perform reliably enough with real data and their wide application to generic hospitals is difficult, since the complexity level of the model construction make them too much “single hospital oriented”. Moreover, they are complex and, in the risk management application the more difficult is the method the least is used by the decision makers. In addition, some of these models specifically focus on a specific aspect of the whole system. For instance many studies include the water system as the only performance indicator of a health facility during earthquakes [35] or they take into consideration non-structural components only without any attention to the structural component. On the other hand, some models are too generic and the hospital is seen just as a node of the “n” elements composing the complex system [42]. Most of the times, the disaster context is not analyzed but just cited as a selection key for choosing the hazard to consider (e.g. earthquakes). Finally, as reported in the ISO standards, a proper risk management process should consider the context analysis and adapt the hospital system within the disaster context and using, as performance indicators, both the strategic and hosting function of health structures.

1.2.4. The Risk Management Chain

1.2.4.1. General

The standardized methodology for risk management proposed within the International PhD program on “Mitigation of risk due to natural hazards on structures and infrastructures” [a], aims to provide a methodological framework to support risk managers in case of disasters which can result in serious damage to building, infrastructure and communities. Given the broad nature of risk, the framework reported in Figure 1.9 was organized for allowing its application to many scenarios. Compared to the ISO standards, the framework is focused on the risk assessment and risk treatment steps without providing any information on the “communication and consultation” and the “establishing the context” phases while the risk identification and risk monitoring are cited but not analyzed. On the other hand, for the “operative steps” the typical modular approach given in [a] provides a clear order and definition of the main actions to be carried out within a risk management process, by providing which specific activities must be done according to the specific purposes (risk analysis, risk evaluation or risk treatment). Moreover, risk analysis is divided in 3 sub-actions which are: the hazard analysis, the damage assessment and the loss assessment. Distinction between damage and loss is necessary in order to apply the framework to systems not uniquely composed by physical elements, but including other dimensions such as economic, human, cultural-social-historical and ecological ones. The model shows how the connection between the hazard analysis and the damage assessment is given by the structural vulnerability while the linkage between the damage assessment and loss assessment is brought by the vulnerability assessment of the whole system. Important aspects regarding with the risk evaluation are the grading phase and the necessity to individuate measurable indicators to prioritize the risk levels. The grading part is essential for the next phase the risk treatment. This is due to the fact that decisions most likely depend on the level of the risk assessed which can be considered acceptable, rejected transferred or mitigated. According to the mitigation sub-step, the mitigating actions can be carried out at different phases of the project implementation or of the cycle of life of the system analyzed. Especially considering the disaster cycle [43], risk reduction activities can be made pre-disaster as prevention for improving resilience (physical) and/or preparedness (organizational) of the system. During the disaster, actions can be carried out with the aim to increase and improve the capacity to cope of the system while after the event measures can be taken for minimizing the recovery time and cost. Finally, the specific terms which are clearly defined in the risk management chain [a], see figure 1.9, allow a precise use and comparison between the different areas of application by avoiding the risk of misunderstanding between, for instance, the scientific and social contexts.

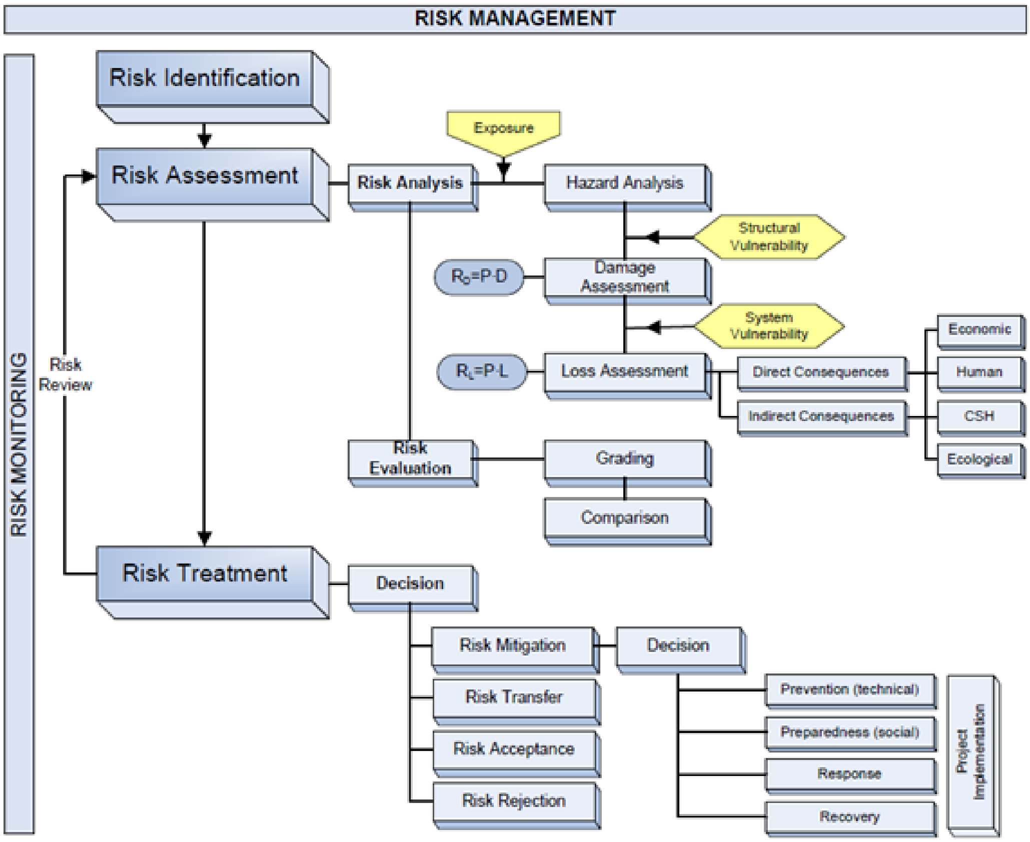

Figure 1.9.: The Risk management chain [a].

1.2.4.2. Application to Hospitals

The aimed development of a methodology for risk mitigation in hospitals according to the risk management chain reported in figure 1.9, must take into consideration the following main steps: risk identification, risk assessment and risk treatment.

a. Risk identification

Earthquake risk is identified as the most relevant risk for hospitals as stated in the WHO/UN international guidelines [30]. Moreover, earthquakes represent the worst case scenario for health facilities since it is responsible for internal and external damages and causing high medical need in the local population.

b. Risk assessment

For the risk assessment two main steps are identified: risk analysis and risk evaluation. As reported in figure 1.10 (red), the risk management process used in this work consist of a hazard analysis by defining the impact of the earthquake in terms of hospital input as local medical demand (earthquake scenario) and the system vulnerability assessment. Risk analysis takes into account the complexity of the system (critical infrastructure analysis) as well as both the structural and non-structural aspects (WHO/PAHO international guidelines for vulnerability assessment) by providing the potential losses in terms of hospital performance degradation. For the risk evaluation, the grading step needs to use specific performance indices in order to have a quantitative evaluation for analyzing the residual hospital capacity (loss assessment) after the seismic impact on the system (hazard analysis).

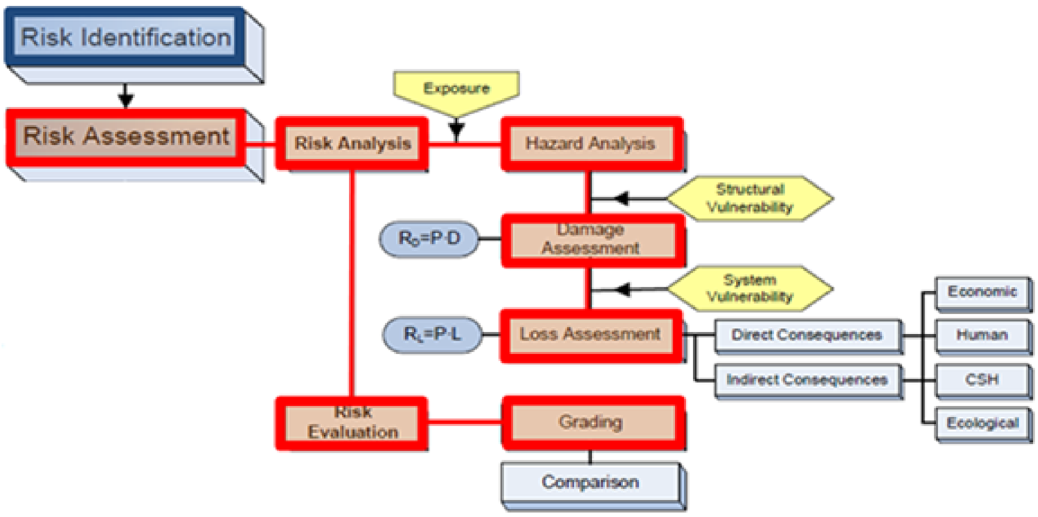

Figure 1.10.: Risk assessment phase proposed for the hospital case.

c. Risk treatment

Once the risk assessment is completed, it is possible to move on to the risk treatment step which includes the risk reduction phase. Since the aim of this dissertation is developing the preventive measures to be taken to mitigate the seismic risk in hospitals, only a partial part of the risk treatment part, reported in the management chain, is analyzed, see figure 1.11. In the decision phase, although all the suggested interventions are preventively planned to reduce the impact of the earthquake, some of them find their application in the coping phase during the acute response phase.

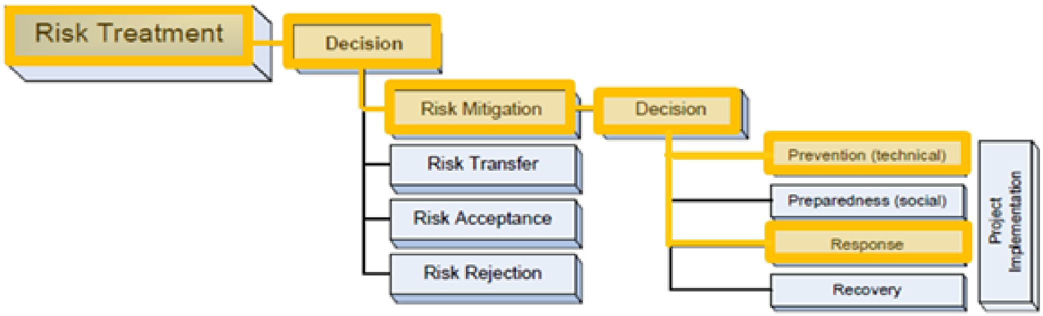

Figure 1.11.: Risk treatment phase proposed for the hospital case.

2. Seismic Vulnerability Assessment

2.1. Overview

The following chapter reports the development of the methodology regarding with the hospital vulnerability assessment. According to the risk management chain applied to the hospital case study, the specific techniques chosen for the vulnerability assessment are described and implemented especially for those methods coming from rapid visual evaluation and the complex system theory. After a first introduction of the rapid seismic evaluation, two different models for the hospital vulnerability assessment are implemented: the Leontief model and the Fault Tree Analysis (FTA). Finally, in order to compare the models, after the estimation of the hospital performances in aftermath of an earthquake, a sensitivity analysis is carried out.

2.2. Rapid Vulnerability Evaluation

2.2.1. General

According to the current state of art, the seismic vulnerability evaluation of health facilities is a process including three main evaluations on structural and non-structural aspects. The Hospital Vulnerability Evaluation (HVE) method proposed by the WHO regional office Europe [27] is a hybrid, mainly qualitative method using rapid visual screening combined with the screener's judgments. The model, integrated with the seismic regulation specification [46, 47], has been chosen for the application to modern hospitals since it is specifically designed for European facilities. As reported in figure 2.1 the evaluation process depends on the seismicity level and it combines evaluation methods for the three main vulnerability categories: structural, non-structural and organizational aspects.

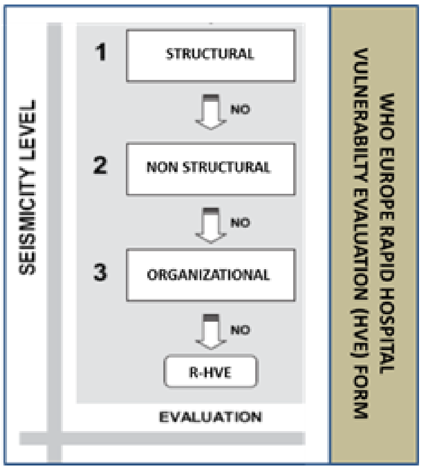

Figure 2.1.: TheHVE method [27].

The rapid visual screening is based on a "sidewalk survey" of buildings, using several data collection forms filled out by screeners. Then, the data are processed and corresponding vulnerability indices, risk ratings or screener judgments, are calculated or assigned in order to evaluate the facility according to structural, non-structural and administrative/organizational vulnerability. Then with the use of vulnerability/performance interrelation matrix, it is possible to get the performance level associated to the correspondent vulnerability grade, see table 2.1.

	Rating		
Vulnerability	Low	Moderate	High
Performance	Good	Average	Poor

Table 2.1.: Vulnerability – performance interrelation matrix [27].

The HVE method takes into account the features distinctive of Europe, such as the predominant building typology used for health facilities, and relies on existing vulnerability assessment methods and the European Macro-seismic Scale (EMS-98)[46] for determining possible seismic demand. Following are described different type of vulnerability evaluation: structural, non-structural and administrative/organizational. Before getting into the structural vulnerability assessment, some general info need to be recorded such as:

- Contacts, name and location of the hospital;
- Number of buildings;
- Clinical specialization in each building.

2.2.2. Structural evaluation

Structural vulnerability is assessed by considering those construction parameters which are easy to be evaluated by the screeners. The parameters are reported as follows:

- General info: Number of stories, type of material and year of construction;
- Structure: Torsional behavior, existing damages, soft story, heavy floor, superimposed floor, short column effect and pounding effect;
- Geology: sloping ground and type of soil. Beginning with the torsional behavior, this is due to the building configuration. In fact, torsion is produced by the eccentricity existing between the center of mass and the center of stiffness and it is the cause of major damage to buildings subjected to strong earthquakes, ranging from visible distortion of the structure (and its resultant loss of image and reliability) to structural collapse.

The *complex or simple building configurations* regarding with the building shape, the plant and the symmetry must be analyzed in order to assess a potential torsional behavior. Figure 2.2 reports the irregular configuration for the symmetry for both axes lateral and longitudinal.

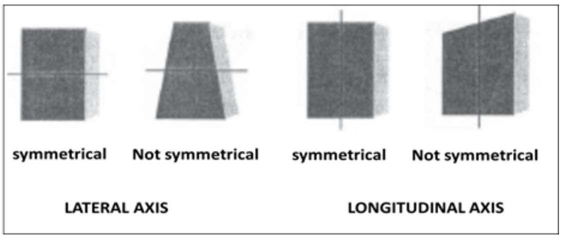

Figure 2.2.: Regular and irregular building configuration [27].

In order to rapidly assess the plan and the elevation simplicity, which are responsible of increasing the torsional behavior of buildings, figure 2.3 reports a sample of the most common simple or complex plans and/or elevation configurations. This should permit an easier and more immediate classification of the screened building which shouldn't necessarily involve expert personnel as screeners.

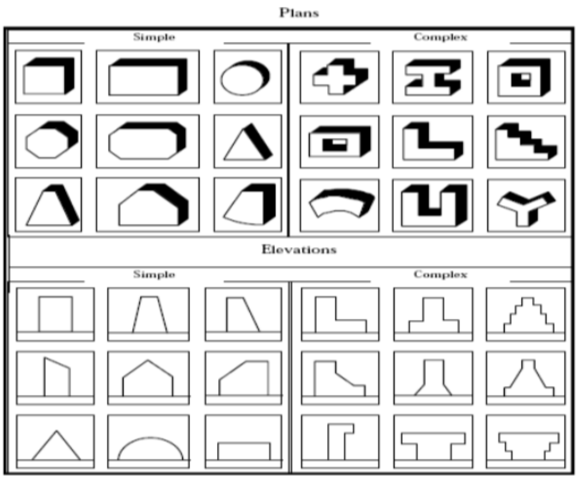

Figure 2.3.: Sample of simple and complex plans and elevation configurations [25].

Moreover, figure 2.4 samples irregular story configuration or non-uniform mass distribution since they could be responsible for potential torsional behavior of the building.

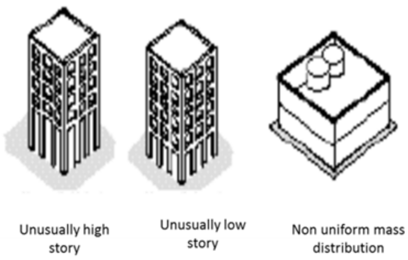

Figure 2.4.: Sample unusually story configuration or mass distribution [25].

Last elements taken into consideration for increasing the torsional behavior in buildings are both the positioning of the stiff elements asymmetrically with respect to the center of gravity of the story and the placement of large masses asymmetrically with respect to stiffness, see figure 2.5.

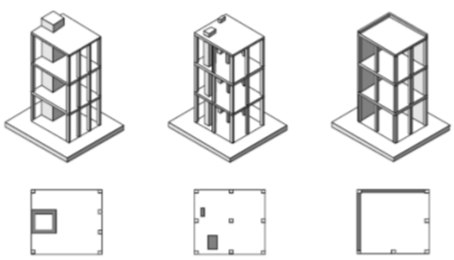

Figure 2.5.: Torsional behavior: asymmetric mass distribution [25].

The next parameter to be assessed for the physical vulnerability is the structural performance degradation which is evaluated by the presence of any *visual damage*. The damage must be considered in accordance to the construction material of the building: masonry or concrete. In masonry buildings, high attention is given to the deterioration of concrete or reinforcing steel in any of the vertical- or lateral-force-resisting elements and deterioration of masonry units. Regarding the masonry joints deterioration, the mortar shall not be easily scraped away from the joints by hand with a metal tool and there shall be no areas of eroded mortar. Finally, there shall be no existing diagonal cracks in wall elements greater than 1/16mm or out-of-plane offsets in the bed joint greater than 1/16 mm. In reinforced concrete buildings, the deterioration of concrete shall be no visible, neither in reinforcing steel nor in any of the vertical- or lateral-force-resisting elements. No deterioration of masonry units shall be visible and for the masonry joints, the mortar shall not be easily scraped away from the joints by hand with a metal tool and there shall be no areas of eroded mortar. In addition there shall be no existing diagonal cracks in infill walls that extend throughout a panel, greater than 1/16 mm, or have out of- plane offsets in the bed joint greater than 1/16 mm. Finally, there shall be no existing diagonal cracks wider than 1/16 mm in concrete columns that encase masonry infill. Another parameter to take into consideration for the visual evaluation assessment is the soft stories effect. Several types of architectural and structural plans lead to the formation of so-called "soft" stories, which are more vulnerable to seismic damage than others due to the fact that they are less stiff, less resistant, or both [25]. The effect depends on the differences in height between floors or/and the interruption of the elements composing the vertical structure of the building, see figure 2.6. The soft storey can be at any level of the building, ground floor (1) and/or at the intermediate level (2).

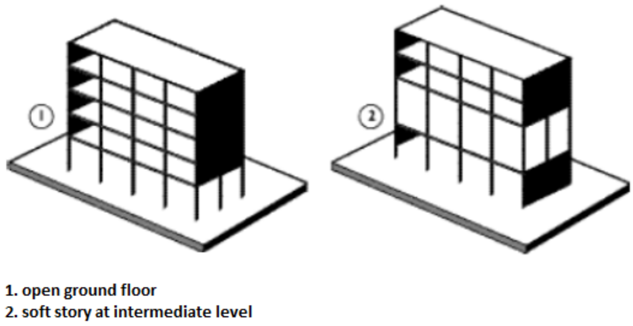

Figure 2.6.: Representation of building affected by the soft storey effect [25.]

Regarding with the *heavy floor effect*, mass irregularities can be detected by the comparison of story weights. The effective mass consists of the dead load of the structure on each level plus the actual weight of partitions and permanent equipment on each floor. The validity of this approximation is dependent upon the vertical distribution of mass and stiffness in the building. Heavy roof/floor can be determined by the analysis of the following points: presence in the floor of heavy walls or of heavy non-structural elements (e.g. presence of heavy equipment or architectural elements such as tanks and antennas on the roof) such as the weight can be estimated as less or more than 50% of the adjacent floors. Furthermore, other aspects which must be considered are the thickness of the floor diaphragm with respect to the adjacent floors and all those elements forming mass irregularities [21]. Moreover, the superimposed floor is a critical situation for the building seismic response similar to the heavy floor/roof and it consists of the addition of a floor after the building construction. Sometimes lack of documentation makes this situation hard to be detected. Only different construction materials or styles make it visible and evident. During past earthquakes, reinforced concrete (RC) frame buildings that have columns of different heights within one storey, suffered more damage in the shorter columns as compared to taller columns of the same storey. Poor behavior of short column is due to the fact that in an earthquake, a tall column and a short column of same cross-section move horizontally by same amount 'Δ', see figure 2.7. However, the short column is stiffer compared to the tall column and gets larger earthquake force. Stiffness of a column means resistance to deformation – the larger is the stiffness, the bigger is the force required to deform it. If a short column is not adequately designed for such a big force, it can suffer significant damage during an earthquake. This behavior is called Short Column Effect. The damage in these short columns is often in the form of X-shaped cracking. This type of damage of columns is due to shear failure within one storey, suffered more damage in the shorter columns as compared to taller columns in the same storey [48, 49].

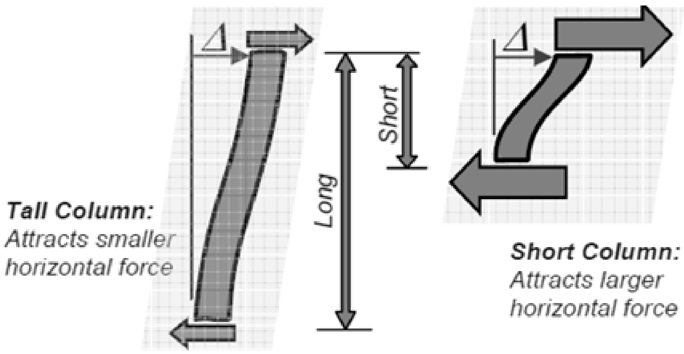

Figure 2.7.: Short column effect [48].

Another element to be considered in the structural assessment is the *pounding effect* between two or more buildings due to the mutual movement caused by the seismic event. This behavior happens when buildings are built without sufficient gaps between them and the interaction has not been considered. The buildings may impact each other, or pound, during an earthquake. Building pounding can alter the dynamic response of both buildings and impart additional inertial loads on both structures. Buildings of the same height with matching floors will exhibit similar dynamic behavior. If the buildings pound, floors will impact with other floors, which means that damage due to pounding usually will be limited to nonstructural components. However, when the floors of adjacent buildings are at different elevations, floors will impact with the columns of the adjacent building and that can cause structural damage. Since neither building is designed for these conditions, there is a potential for extensive damage and possible collapse [21], see figure 2.8.

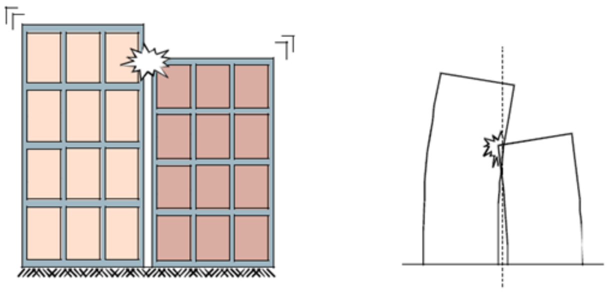

Figure 2.8.: Pounding effects due to the seismic event [21]

Ground and geological aspects are important as well for the building seismic behavior [21]. A *sloping ground* is clearly more dangerous for the buildings than a flat one. One damage situation is represented by the necessity to use short columns to build flatly floors in sloped grounds, see figure 2.9.

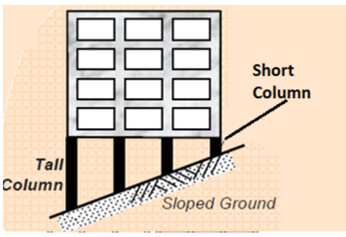

Figure 2.9.: Slope ground effect on the building seismic behavior.

Moreover, geological aspects are important also for what concerns the composition of the ground where the building is located. Indeed, this is responsible for the seismic energy propagation and amplification. According to the EC-8 definition [47], three main soil types are classified:

1. Rock/hard soil condition: The geology least prone to cause damage to structure by earthquake shaking;
2. Medium soil condition: Prone to moderate shaking;
3. Soft soil condition: Behaves like jello by magnifying earthquakes waves.

Figure 2.10 and 2.11 report the structural evaluation forms suggested by the WHO/Europe [27] which depend on the building type: masonry or reinforced concrete respectively.

Building type		Vulnerability indices/modifiers			
		M1.2	M3.1	M3.4	M5
Basic vulnerability index		37	37	31	35
Maintenance	Good	–2			
	Bad	+2			
No. of storeys	1–2	–1			
	3–5	+1			
	6+	+3			
Soft storey		+2			
Plan irregularity		+2			
Vertical irregularity		+1			
Superimposed floors		+2			
Heavy roof		+2			
Retrofitting interventions		–2			
Ground slope		+1			
Soil conditions	A	–2			
	B	0			
	C	+2			
TOTAL VULNERABILITY INDEX =		VULNERABILITY LEVEL = Low/Moderate/High			
Comments:				Detailed evaluation required YES NO	

Figure 2.10.: Structural evaluation form for masonry buildings [27].

Building type		Vulnerability indices/modifiers						
		RC1	RC2	RC3.1	RC3.4	RC4	RC5	RC6
Basic vulnerability index		20	17	20	26	17	17	25
Period of construction		Pre-1970		1970–1980			Post-1980	
Code level		+8		0			–8	
Maintenance	Good	0		0			0	
	Bad	+2		+1			0	
No. of storeys	1–3	–2		–2			–2	
	4–7	0		0			0	
	8+	+4		+3			+2	
Plan irregularity	Shape	+2		+1			0	
	Torsion	+1		+1			0	
Vertical irregularity		+2		+1			0	
Soft storey		+3		+2			+1	
Short columns		+1		+1			0	
Type of foundation	Beams	–2		0			0	
	Concrete beams	0		0			0	
	Footings	+2		0			0	
Ground slope		+1		+1			+1	
Soil conditions	A	–1		–2			–2	
	B	0		0			0	
	C	+2		+1			+1	
TOTAL VULNERABILITY INDEX =		VULNERABILITY LEVEL = Low/Moderate/High						
Comments:						Detailed evaluation required YES NO		

Figure 2.11.: Structural evaluation form for reinforced concrete buildings [27].

Finally, for the structural vulnerability grading is important to assess the expected damage during earthquakes. Indeed, by defining the seismic effects on the hospital it is possible to correlate the expected average damage μ_D with the magnitude classification reported by EMS-98 [46], the vulnerability level assessed (TV_I) and the specific seismic intensity (I), see equation below.

$$\mu_D = 2.5 \times [1 + tanh(I + 0.25TV_I - 13.1) \div 2.3] \quad (1)$$

TV_I depends on the seismic building behavior [50] while µD depends on I and TV_I. Once obtained the correspondent μ_D to specific "I," the damages can be connected to the Total Vulnerability Index by following the ems-98 damage grades classification. And by using table 2.2, it is possible to obtain, by using the μ_D value, the estimated hospital performance (low, moderate, high).

Seismic intensity	Vulnerability level		
	Low	Moderate	High
1	< 89	89–105	> 105
2	< 81	81–97	> 97
3	< 73	73–89	> 89
4	< 65	65–81	> 81
5	< 57	57–73	> 73
6	< 49	49–65	> 65
7	< 41	41–57	> 57
8	< 33	33–49	> 49
9	< 25	25–41	> 41
10	< 17	17–33	> 33
11	< 9	9–25	> 25
12	< 1	1–17	> 17

Table 2.2.: Correlation table between TV_I and performance level.

2.2.3. Non-structural evaluation

The rapid evaluation forms for non-structural aspects [27, 25, 21] include one form for medical equipment and office furniture, one form for the basic installations and one form for the architectonics and facades elements. Since in literature the forms regarding medical equipment and basic installations are not detailed, two new forms have been designed and added for a rapid non-structural vulnerability evaluation. Table 2.3 reports the form for installations and systems vulnerability evaluation. It takes into consideration the presence of the necessary elements for an appropriate hospital performance and the subsequent risk to a seismic event. The risk is classified according to the severity of subsequences to the damage: life affecting (V), economic loss (D) and operational loss (O).

Installations and systems form	Presence	Risk level		
		V	D	O
Medical Gas				
Cylinders				
Tanks				
Compressors Distribution net				
To be evaluated: *Fixing level for cylinders (yes - partial - no)* *Fixing level for pipes (yes - partial - no)* *Safe cylinders strorage (yes - partial - no)* *Linkages (flexibility and resistance)*				
Power distribution				
Switchboards				
UPS				
Back up generator				
Power net				
Diesel tanks				
To be evaluated: *Fixing level for back up generator (yes - partial - no)* *Net and linkages elements (flexibility and resistance)* *Protectiona and insulation of diesel tanks (yes - partial - no)*				
DATA (HIS)				
Antennas				
Distribution net				
Power				
Devices				
To be evaluated: *Devices fixing level (yes - partial - no)* *Net and linkage amongst elements (flexibility and resistance)* *Redundancy* *Critical elements protection*				
Plumbingsystem				
Pipes				
Tanks				
To be evaluated: *Tanks fixing level (yes - partial - no)* *Pipes fixing level (yes - partial - no)* *Net and linkage amongst elements (flexibility and resistance)*				
Viability				
Elevators				
Air rescue				
Ambulances				
Emergency exits				
Signs				
Lighting and emergency illumination				
To be evaluated: *Elements fixing level (yes – partial - no)* *Redundancy* *Critical elements protection*				
Firesystem				
Water tanks				
Power				
Sprinkler				
Detectors				
Estinguishers				
Fire door (REI)				
Signs				
To be evaluted: *Elements fixing level (extinguishers and tanks) (yes – partial - no)* *Pipes fixing level (yes – partial - no)* *Connections an linkage amongst elements (flexibility and resistance)* *Redundancy* *Elements protection*				

Table 2.3.: Lifeline and basic installation vulnerability evaluation form.

Regarding the medical devices vulnerability evaluation, the form is reported in table 2.4. It takes into account the presence of specific medical devices by classifying them according to the destination of use: big therapeutic - diagnostic devices and life support or emergency use equipment which defines those devices essential for the hospital treatment activity during earthquakes.

Big devices	**Fixing level** (yes-partial-no-no device)
CT	
Linear accelerator	
Hyperbaric Chamber *	
Radiography system	
Mammography system	
Gamma chamber	
PACS – DICOM System	
Radioscopy system	
Radiotherapy system	
MRI system	
TAC	
PET	
Autoclave	
Surgical microscope	
Anaesthesia system	
Pulmonar ventilator	
Freezer units	
Incubator	
LIFE SUPPORT – EMERGENCY	**Fixing level** (Yes-Partial-No-No Device)
Microscope	
Central monitor system	
External pacemaker	
Infusion pump	
Blood freezer unit	
Scialitic lamp	
Portable scialitic lamp	
Pulmonary ventilator	
Respiratory system	
Operating table	
Defibrilator	
Portable vacuum	
Ultrasound device	
Oxigen cylinders	
Patient Monitors	
Emodyalisis apparatus	
Emergency cart	
Negative pressure ventilator	
Gas analyzer	
Pulsoximeter	
Electro surgical instrument	
Cardiomonitordefibrilator	

Table 2.4.: Medical equipment evaluation form for vulnerability assessment.

According to the international guidelines described in chapter 2 [27-21] and the scientific literature [36, 51-55], it was found out that the level of performance of medical equipment is strongly related to the level of fixing or anchorage to the floor or to the walls pre event. Hence, for each listed device, the form takes into consideration the quality of any fixing system applied to the device itself by the use of three levels: “yes” for good quality fixing,” partial” for not adequate fixing and “no” for any type of fixing applied to the medical device. The term “no device” means that the medical equipment is not present in the hospital area.

2.2.4. Administrative/organizational evaluation

For the organizational vulnerability, the medical and clinical procedural planning aspects must be considered. Especially for the medical treatment areas, a priority index amongst the different clinical activities must be defined in order to properly coping the emergency phase. According to the Pan American Organization [25], table 2.5 defines priority index of each medical service which can be rated as: (1) dispensable, (2) preferable, (3) necessary, (4) very necessary and (5) indispensable in an emergency situation.

Clinical and support services	Importance rating
Trauma and orthopaedic	5
Intensive care unit	5
Urology	5
Emergency care	5
Sterilization	5
Diagnostic imaging	5
Pharmacy	5
Nutrition	5
Transport	5
Recovery	5
Blood bank	5
Outpatient consultation/admission	4
Paediatric surgery	4
Paediatrics	4
Laboratory	4
Haemodialysis	4
Laundry services	4
Internal medicine	3
Gynaecology and obstetrics	3
Administration	3
Neonatology	3
Respiratory medicine	2
Ophthalmology	2
Filing and case management	2
Dermatology	1
Psychiatry	1
Oncology	1
Otorhinolaryngology	1
Dental services	1
Therapy and rehabilitation	1

Table 2.5.: Priority definition of clinical activities during disasters [25].

The subsequent designed form is reported in table 2.6. Number of beds and operating tables are essential information for estimating the ordinary hospital performance and the potential degradation in aftermath of an earthquake. Detailed explanation and definition on performance level will be given in the next paragraphs .The "building ID" permits to connect the medical activity to the specific seismic behavior of the building.

MEDICAL AREA	OPERATING TABLES	BEDS	BUILDING ID
Surgery rooms			
Inpatient ward			
Imaging			
Laboratory			
Blood bank			
ICU			
Emergency department t			

Table 2.6.: Evaluation form for organizational vulnerability .

Moreover in the organizational vulnerability area, the remaining details must be assessed:

- Appropriate number of personnel in relation to the estimated working load;
- Documentation (building certificates, maintenance reports, emergency plans, etc..);
- Personnel training (drills and exercitations).

2.2.5. Fire vulnerability assessment

Given the fact that in hospitals many occupants are non-self-sufficient people and they can't autonomously move because of their temporary or permanent physical disability or the necessity (for some of them) to be life-dependent on technology support, a particular attention to fire risk assessment in hospital must be paid. According to the scientific literature, the research focused on the phenomena regarding the "Fires Following Earthquakes (FFE)" in Hospitals [56-75] which demonstrates how the fire risk increases after an earthquake. Moreover fire risk can determine the loss of very expensive equipment and the interruption of the clinical activity. So, in order to resume the severe subsequence of fire in hospitals, the severity is assessed as follows:

- Difficulties for the evacuation of not self-sufficient people;
- Loss of very expensive equipment;
- Continuity of the main clinical activities.

For the reasons above, a new form was designed with the aim to assess the fire vulnerability in health structures after a seismic event, see table 2.7. The FFE vulnerability assessment form is divided in four main sections: ignition, evacuation, protection and suppression vulnerability.

		FIRE FOLLOWING EARTHQUAKES RISK			
Id Area					
Id Building		IGNITION VULNERABILITY FORM			
Destination of use		**gas fixing systems**		**liquids cupboards fixing**	
ICU		Gas not present		liquids or cupboards not present	
Inpatient ward		Present and not fixed		Present and not fixed	
Technical area		Present and fixed		Present and fixed	
...		**electric fixing systems**		**O2 fixing systems**	
N° of Occupancy		Electric system not present		O2 not present	
< 10		Present and not fixed		Present and not fixed	
10- 50 pp		Present and fixed		Present and fixed	
50pp		**heavy equipment fixing systems**		**gpl fixing systems**	
regulation compliance		Equipment not present		GPL not present	
yes		Present and not fixed		Present and not fixed	
not		Present and fixed		Present and fixed	
partially		EVACUATION VULNERABILITY			
Signage		**Emergency light**		**No panic doors**	
yes		yes		yes and width enough	
no		no		yes and not width enough	
partially		partially		no	
Strorey level		**warning alarm**		**smoke detectors**	
ground		yes		yes	
1st or -1st		no		no	
2nd - 3rd		partially		partially	
> 3rd		PROTECTION VULNERABILITY			
automatic sytems		**materials**		**Compartmentation**	
selfing closing doors		fire resistant		opening	
smoke detectors		not fire resistant		rei door presence	
heat detectors		unknown		safe area definition	
air system dampers installation		SUPPRESSION VULNERABILITY			
splinkers		**manual systems (extinguishers)**		**brigades**	
yes		yes		yes and easy to access	
no		no		yes and not easy to access	
partially		partially		no	

Table 2.7.: Fire Following Earthquake (FFE) vulnerability evaluation form.

Each form corresponds to a specific destination of use located in a specific area of the building. This permits to compare collected data with the referring values reported in table 2.8 which suggests which medical activity must be placed to the ground floor in relation to the occupants' safety and security. Moreover, the appropriate types of specific warning alarms (WA), according to the medical areas, are indicated in table 2.8 as well.

Once all the vulnerabilities assessments have been completed (structural, non-structural, organizational and fire risk) for each hospital building, the remaining part for a proper system vulnerability assessment especially for modern hospitals, consists of understanding how all the different area and parts are mutual connected and how a damage or degradation can propagate in the system and causing what kind of degradation in the hospital performance The application of the critical infrastructure theory especially for what concerns the complex system modeling has been applied to the hospital case study as described in the following section by the application of two different models: the input-output inoperability Leontief model and the Fault Tree Analysis.

destination of use	*Internal area distribution*	*Ground floor*
ICU	street level	WA
Nursery	street level	
OR	street level	WA
DR	street level	
stores		WA
workshops		
kitchen		heat detector
electrical central		WA
laundry		heat detector
waste storage		WA
pharmacy		
medical gas storage		WA
lpg storage		WA
changing rooms		WA
morgue		
diagnostic		WA
Central Sterilization		
Obstetrics		WA
Psychiatric wards		photo electric
geriatric wards		photo electric
paedriatic wards		photo electric
physiotherapy		WA
staff accomodations		WA
exit paths and corridors		photo electric

Table 2.8.: Suggested floor level and warning alarms according to the specific medical area.

2.3. Hospital System Analysis

2.3.1. Overview

A hospital is considered a complex system [32, 50]. According to the scientific literature two main models have been chosen to analyze the hospital system: the

Leontief model and the Fault Tree Analysis [32, 34, 36]. In the following paragraphs both models are developed according to the hospital system characteristics.

2.3.2. The Input - Output Inoperability Leontief Model

2.3.2.1. General

Hospitals are complex systems defined as critical infrastructures. With the term “Critical Infrastructure” is intended that part of the socio-economic system on which functions that sustain life, commerce and human activities depend. It is critical in the sense that the failure of any of its principal components can lead to knock-on effects upon other systems. For example, loss of electrical power can compromise many systems from, railways to traffic lights, and thus lead to progressive break-down of the socio-economic system. Critical infrastructures usually have weaknesses, or points of maximum vulnerability, which are especially susceptible to failure, or that represent points where failure would have the greatest consequences. The Leontief model enables one to analyse critical infrastructures in conjunction with one another and to test hypotheses about the knock-on effects of failure. It is thus a powerful tool for the study of vulnerability in terms of cascading failures and their potential consequences. A critical infrastructure is operationally defined as a complex system formed by its own structure, technologies and personnel. When it is temporarily interrupted it can significantly disturb a society at the local, national and even international levels. In recent years these social and technological infrastructures have become increasingly complex by forming mutual dependencies and interdependences, especially with an increasing use of information technology and communications. Improvement in the quality of services and reduction in costs can lead to the emergence of new and unforeseen vulnerabilities. Closely linked infrastructures tend to be highly vulnerable to the propagation of faults. A failure in one part of the network can easily spread by a "domino effect" mechanism throughout the whole system with impacts on its functionality and geography. This can amplify the effects and cause malfunctions and failures that affect even remote users, as may occur, for example, in a health system. The Wassily Leontief model on the balance of economic systems forms the basis of the input-output model of inoperability (IIM Inoperability Input-Output Model) that was developed by Yacov, Haimes and Jiang (2001) and is used for complex infrastructure analysis. The application of this model to the description of complex systems such as hospitals aims to simulate their behaviour in case of an external event or failure by carrying out a vulnerability assessment that takes into consideration how a specific failure can influence functionality of the whole system. Furthermore, this tool allows stakeholder opinions and experience to be taken into account and thus improves the more reliability of the model of the system. The model describes a method for analyzing the impact of an event (i.e. a failure) and its propagation to connected systems by estimating the impact of the initial event on the operations of the infrastructure.

It takes into consideration the elements that make up the system, together with their mutual interdependencies. It does so by considering the direction of functional impacts (element “a” is essential to the performance of element “b,” but element “a” is not influenced at all by the operational level of element “b”). In other words, the model aims to analyze how the inoperability of one part of the system (i.e., its inability to perform tasks that it is directed to do) is propagated to the other system elements. The model quantifies the subsequent inoperability of the infrastructure, where ’inoperability of a system’ is defined as its inability to perform completely its proper functions. The inoperability is quantified as a value between zero and one, where zero corresponding to a perfect performance at the operational level and one refers to complete ineffectiveness of the system (i.e., 100% inoperability). Yacov, Haims and Jiang (2001) defined the input-output model as follows:

- x_j - overall risk of ineffectiveness of the jth interconnected infrastructure that can be caused by one or more failures;
- r_i - the i^{th} resource to manage the risk of ineffectiveness of the specific critical infrastructure due to the general complexity of the system;
- x_{kj} - the degree of subsequent ineffectiveness of the k^{th} infrastructure due to one or more multiple failures caused by the j^{th} interconnected infrastructure element;
- a_{kj} - a weight representing the influence that the jthinfrastructure has on the ineffectiveness of the interconnected k^{th} infrastructure, due to the type and strength of their interconnection: its values form the interdependencies coefficient of matrix A.

Haims and Jiang also consider $a_{kk} = 0$ for $\forall$ k, so as to exclude from the Leontief matrix all those effects caused by the failure of the infrastructure upon itself. Furthermore, the vector of failures c is defined as the percentages of inoperability of all the elements k of the system at the initial time t=0 due to the external disturbance at the system by factors such as natural disaster or accidents. The basic equation of the Leontief model is given in the following equation 2:

$$X_k = \sum_{k=1}^{n} a_{kj} x_j + c_k \quad (2)$$

The next expression deals with the same model using the matrix form (3):

$$\begin{pmatrix} x_1 \\ ... \\ x_n \end{pmatrix} = \begin{pmatrix} a_{11} & ... & a_{1n} \\ ... & ... & ... \\ a_{n1} & ... & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ ... \\ x_n \end{pmatrix} + \begin{pmatrix} c_1 \\ ... \\ c_n \end{pmatrix} \quad (3)$$

Equation (4) gives the synthetic form:

$$X = AX + c \quad (4)$$

in which all the elements are non-negative (0≤ X_i ≤1). By assuming that matrix (I-A) is not singular, equation (4) can also be written as follows:

$$(I - A)\,X = c \quad (5)$$

The subsequent degree of ineffectiveness can be calculated as follows:

$$X = c\,(I - A) - 1 \quad (6)$$

By using the matrix form reported in equation (7):

$$X = (I - A)^{-1}\,c = \left[\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} a_{00} & a_{01} & \dots & a_{0n} \\ a_{10} & a_{11} & \dots & a_{1n} \\ \dots & \dots & \dots & \dots \\ a_{n0} & a_{n1} & \dots & a_{nn} \end{pmatrix}\right]^{-1} \begin{pmatrix} c_0 \\ c_1 \\ \dots \\ c_n \end{pmatrix} \quad (7)$$

When the system is in perfect condition, or under conditions in which all components are operating fully, we have $x_k = 0$ for every k and $\sum x_k = 0$.

The last step is to determine the coefficients of the input-output matrix. This is the most difficult part of the modelling process, and will now be described in detail. Matrix A plays a central role in defining the problem and some indicators can be defined in order to characterise it. The first of these is the dependency index, which is defined as follows:

$$\delta_i = \textstyle\sum_j a_{ij} \quad (8)$$

This is unique for every element or infrastructure that comprises the general system. It is calculated as the sum of row elements in matrix A, and it gives a measure of the strength of the i^{th} element compared to the inoperability of all others. A dependency index of less than one means that the infrastructure still preserves some operational capability in spite of the overall ineffectiveness of the system. In contrast, an index of inoperability greater than one indicates that the specific element or infrastructure is strongly dependent to other elements or infrastructures and can be totally ineffective as a result of the ineffectiveness of other elements.

The second indicator represents the influence that a specific infrastructure has on the entire system: the influence gain. It is defined as the column sums of matrix A coefficients. The influence gain provides a measure of how critical the services of the specific infrastructure are to the functionality of other system elements. A high index of dependency indicates that inefficiencies of a specific infrastructure, even when they are small, exert a strong influence and can lead to the inoperability of other infrastructures. A low value means that the ineffectiveness of the j^{th} infrastructure has little effect on the operational capacity of the others.

$$\rho_j = \textstyle\sum_i a_{ij} \quad (9)$$

Finally, it is important to highlight that the use of the Leontief model implies that a unique non-negative solution exists.

2.3.2.2. *Analysis of interdependencies*

One of the most critical steps in building the input-output inoperability model is to determine the coefficients of the Leontief matrix A. In order to obtain a complete and reliable model it is essential to perform a thorough analysis of interdependencies among the infrastructures. In other words, the interdependency term must consider any type of dependency between two or more infrastructures. In order to evaluate the hospital performances in aftermath of an earthquake, the critical path strategy has been followed which consists of considering only the medical areas rated as "indispensable" reported in table 2.5 [25] (from element "A" to element "G) besides the technical systems and medical equipment (from element "H" to element "R"). A total of sixteen elements have to be considered in the Leontief Model development for seismic vulnerability assessment as follows:

1. Emergency department;
2. Diagnostic & Lab;
3. Surgical operation;
4. ICU;
5. Inpatient ward;
6. Morgue;
7. Special assistance (urology, pediatry,etc..);
8. Chrisis room;
9. Internal connection (lifts, viability, etc..);
10. Power network;
11. Gas network;
12. Hydric network;
13. HIS;
14. Fire system;
15. Equipment;
16. Accessibility.

One of the main approaches to analyzing complex interdependencies and subsequent definitions of the Leontief matrix coefficients is agent-based modelling. The basic idea behind this approach is to model the general system by using a 'bottom-up' analysis. The modelling process includes study of the behavior of the individual components and the trajectory of the whole system when these components start to interact. In this context, the individual components are defined as single entities characterised by location, capacity and memory. The location of an entity is defined as the physical space in which it is located. The capability of an entity expresses what it is able to do. The memory represents its current state and operational history, such as its propensity to overload or aging. An alternative approach is based on building a knowledge base through the compilation of technical questionnaires. In particular, technical information is gathered through a series of questionnaires submitted to experts. By considering different durations of failure, the questions seek to understand the dynamics of failure propagation and the impact that failure in a specific infrastructure will have on the others. Hence, in order to ensure the correct interpretation of uncertain data, the methodology uses a fuzzy logic system that takes into consideration both the experience of the user and the degree of confidence placed in the answer.

2.3.2.3. *Fuzzy logic questionnaire*

A fuzzy logic questionnaire has been developed for the determination of the Leontief coefficients a_{ij}. The values obtained are weighted on both experts' certainty and expertise, see figure 2.12. The value a_{ij} is comparable to a triangular area where the mean value at the base represents the chosen value by the expert, the base width depends on the grade of certainty while the height is defined according to the expertize level of the interviewed.

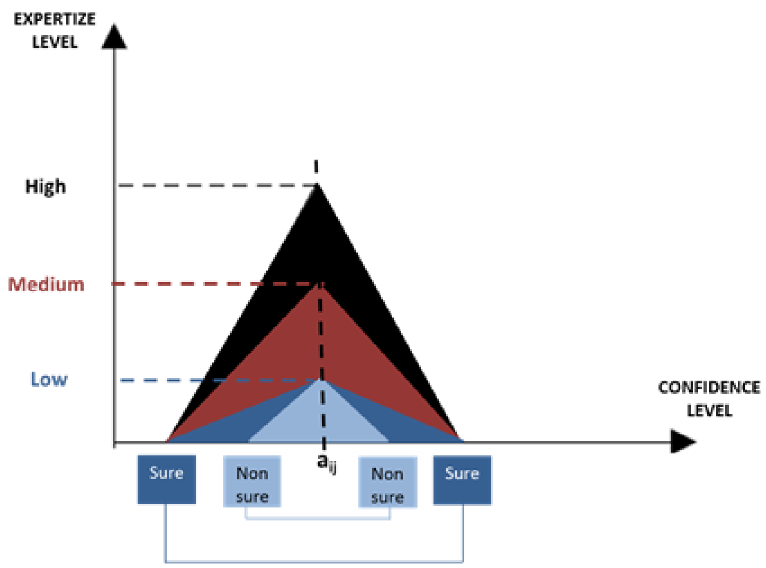

Figure 2.12.: Triangular value according the fuzzy logic theory.

Every expert's interview is described by a specific membership function which is combined with the others' functions in order to get one general value for opinion, see figure 2.13. The general value is obtained by combining the red and the blue functions.

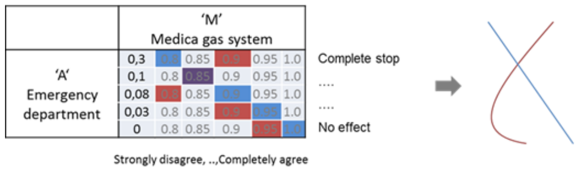

Figure 2.13.: General value as combination of membership functions.

Once the interviews are completed, a validation process is necessary to control if the obtained coefficients are all acceptable as similar to the general trend or if the general output is just a mathematical result. The statistical analysis chosen for the validation consists of a t-test (ANOVA and Fisher Least Significant Difference) applied to both the experts and to the opinions in order to declare which values can't be acceptable.

2.3.2.4. *The Input Inoperability vector*

The input inoperability vector represents the level of inoperability of the hospital systems after an earthquake and it is the input to the Leontief model. The definition of the inoperability vector depends on the vulnerability level assessed by the evaluation forms at a specific seismic magnitude. The degradation levels used to define the hospital area performance in the aftermath of an earthquake are as follows [32]: high vulnerability= 0.3, medium vulnerability=0.1 and low vulnerability = 0.03. Finally, figure 2.14 summarizes the Leontief model structure and the procedure to carry out.

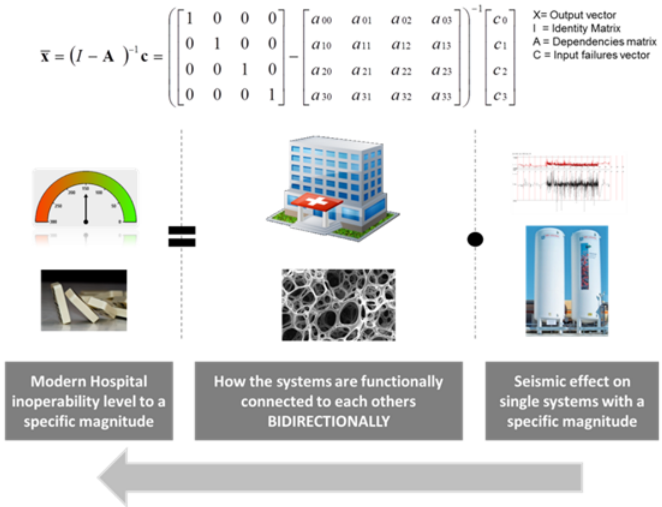

Figure 2.14.: Leontief model application.

From right to left in the picture, firstly it is the inoperability vector definition by the rapid vulnerability evaluation forms, secondary is the questionnaire interview for the matrix "A" coefficients' definition. The output vector is the hospital system inoperability with all the degradation degrees for each medical area.

2.3.3. FTA Model

The Fault Tree Analysis (FTA) is a top-down, deductive failure analysis in which the reliability of a System (Top Event) is assessed by using a boolean logic to combine a series of basic simple events (the fault's leaves) [76]. The FTA was originally developed in 1962 by the Bell Laboratories by H.A. Watson for military purposes. Following the main FTA applications have been regarding to complex systems analysis such as civil and military aircrafts' equipment and the nuclear power industry. Safety and reliability aspects are the main application fields of the Fault Tree Analysis. FTA in reliability Engineering can be used for designing safely systems (by identifying potential causes of failure) and for systems' breakdown prediction and diagnosis. Moreover, the FTA allows investigating the consequences of an initial event to the top event of the system analyzed. In other words, by the failure probability of the basic elements, the top event probability of failure is estimated by taking into consideration the elements distribution as well. Hence FTA is used to calculate the overall probability of failure of a system with the reduction of the system to a group of both serial and redundant sections. The presence of parallel elements makes the system more reliable and the probability of failure decreases, see figure 2.15a. On the other hand, the presence of serial elements' distribution in the general system makes the top event probability of failure increasing, see figure 2.15b.

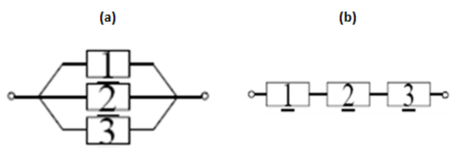

Figure 2.15.: Fault Tree Analysis configuration. (a) Parallel distribution; (b) Serial distribution.

With the term Reliability 'R' is intended the total number of working pieces divided by the total number of pieces checked out. The relationship between the Reliability 'R' and the Unavailability 'Q' of an element is described in equation 10:

$$R = 1 - Q \quad (10)$$

The mathematical formulas to estimate the top event reliability depends on the elements' distribution, parallel or serial. In figure 2.16a is reported the calculation in case of parallel system (AND boolean operator) while in figure 2.16b is reported the serial configuration (OR boolean operator).

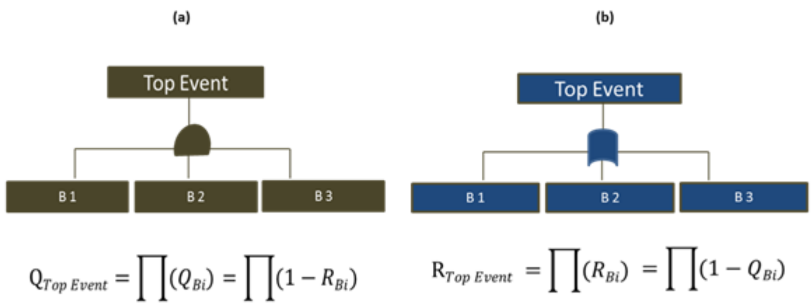

Figure 2.16.: FTA boolean calculation. (a) parallel system; (b) Serial system.

For a hospital system, the top event concerns the combination of different hospital areas. As reported in figure 2.17, each hospital area performance depends on structural, non-structural and organizational components. Furthermore, non-structural component depends on basic installations, medical equipment and architectonics reliability levels. The basic installations considered in the FTA hospital application include the fire safety, the power distribution, the plumbing system, the medical gas distribution and the internal and external viability. Each basic event failure probability is statistically independent of the others and each single failure probability of the basic events is estimated by the field data collection by using the evaluation forms described in the previous paragraphs. The values related to the vulnerability levels assessment are as follows [32]: High vulnerability = 0.3, Medium = 0.1 and Low vulnerability = 0.03.

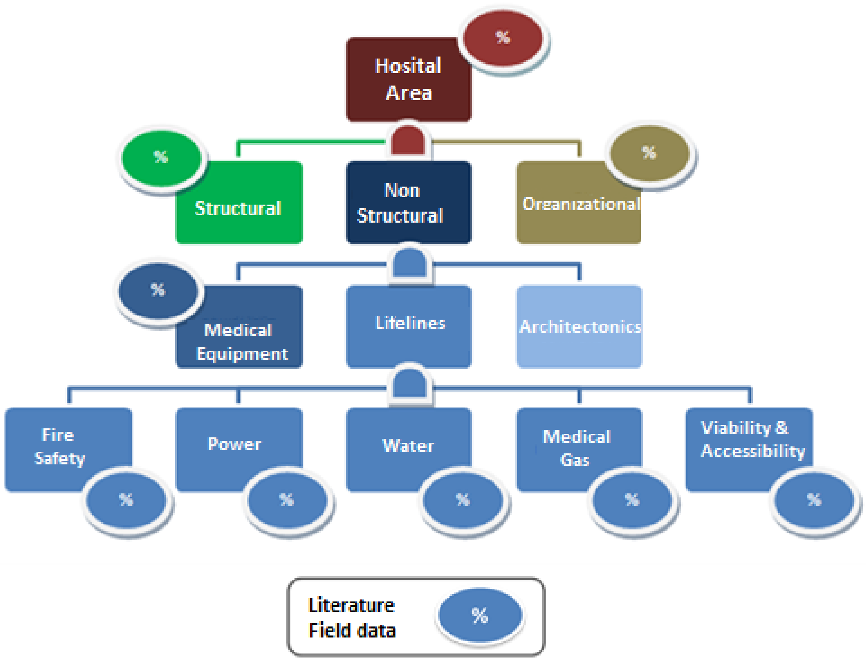

Figure 2.17.: Hospital FTA.

2.4. Hospital Performance Evaluation

Once the hospital system is defined and the evaluation forms are ready to be applied in the field application, last step of the system vulnerability assessment is the definition of quantitative indicators which can be used as measurement of the hospital performance. This permits to quantitatively determine the vulnerability level by calculating its degradation as performance loss. According to scientific literature [77, 36], the hospital performance can be assessed by the use of the Hospital Treatment Capacity (HTC) which is defined as the number of surgical operation feasible per hour by the hospital, see equation 11. The coefficients α and β define the staff and organizational functionality (0-1), γ_1 is the number of surgery tables, γ_2 is the surgery room performance (0-1) and $\mathrm{T_m}$ is the time necessary for a single treatment.

$$HTC = \alpha \times \beta \left(\gamma_1 \times \gamma_2\right) \div T_m \quad (11)$$

In order to evaluate the index above, it is necessary to estimate the operating theaters' performance by the reliability analysis of the appropriate medical areas and the basic installations including the medical equipment availability. This calculation only considers the strategic function of the hospital without considering the intrinsic security of patients inside the structure. Especially for hospitals, this aspect should be assessed as well because of the high presence of not self-sufficient people 24 hours per day. Hence, a new index called Intrinsic Security (IS) has been developed, see equation 12:

$$IS = \alpha \times \beta \times \left[\left(\gamma_3 \times \Gamma_2\right) + \left(\gamma_4 \times \rho_2\right)\right] \div \left(\gamma_3 + \gamma_4\right) \quad (12)$$

Where the coefficients Γ_2(0-1) and ρ_2(0-1) define the performance of the in-patient and ICU areas respectively. The evaluation of the hospital intrinsic security shall consider both inpatient and ICU beds. For the inpatient beds (γ_3) is necessary to evaluate structural vulnerability and the fire safety according to direct risk and unsafe evacuation. For the ICU beds (γ_4), besides the structural vulnerability and the fire safety, essential role is played by medical equipment and basic installations as well. Patients connected to life support devices and difficult to move represent the most critical situation in terms of intrinsic risk in hospitals.

3. Seismic Risk Assessment

3.1. Overview

As reported in the glossary, the risk assessment formula chosen in this dissertation is given by the combination of system vulnerability (V) and the considered hazard (H), see equation 13:

$$RISK\,(R) = Vulnerability\,(V) \times Hazard\,(H) \quad (13)$$

For this reason, the hospital risk assessment methodology developed aims to complete first the system vulnerability assessment procedure and next to include the evaluation of the seismic impact on the health response performance. This is essential in order to find out the necessary procedures for the further risk mitigation.

3.2. Hazard Analysis

According to the risk management chain, the hazard analysis can be completed with the loss assessment obtained from the hazard impact analysis on both the local context (number of casualties) and the hospital system (performance degradation). In order to assess the seismic impact on the medical context, the number of severe injured people which need surgical care after an earthquake is considered. Many indices existed such as the Hospital Surgical Capacity (HSC) [28] which is the number of seriously injured patients that can be operated upon within a 12-hour period or the Hospital Treatment Demand (HTD) [77]. Another index, the Hospital Treatment Demand (HTD), has been chosen because it is easier to be evaluated by considering the estimation of the total number of yellow and red tagged injured as defined in equation 14:

$$HTD = j \times N_{T1+T2} \quad (14)$$

Where T1 and T2 are the red and yellow tagged injured people respectively during the triage while “j” is a constant considering which proportion of patients classified as T1 and T2 needs surgical intervention. According to the literature [36] a value of J=1/3 has been considered in this study.

Furthermore, in order to quantify the amount of surgical demand per specific hospital, a new index $\mathrm{HTD_{HOSPITAL}}$ has been developed. It is evaluated under the hypothesis to have a uniform distribution of casualties' hospitalization and measures the medium horary surgical load per hospital. As reported in equation 15, the index takes into consideration ten hours as the acute emergency period. This choice is due to the fact that this dissertation aims to analyze the hospital performances in aftermath of the disaster only.

$$HTD_{HOSPITAL} = [(HTD \div number\,of\,hospitals) \div 10\,hours] \quad (15)$$

The only question still open is whether the capacity of the hospital system in aftermath of a seismic event will be able to successfully satisfy the local medical need. In order to answer this question, the next section describes how to quantify and analyze the residual hospital performance assessment at a specific seismic condition.

3.3. Risk Assessment

In order to analyze the hospital capacity of treatment in a specific seismic scenario, the HTC is divided by the $\mathrm{HTD_{HOSPITAL}}$and provides a sort of indicator which is able to provide a numerical estimation on the capacity of the hospital to comply with the local health demand, see equation 16. The new index is called the Hospital Treatment Capacity Indicator (HTCI) and when the medical needs are complied, the HTCI assumes the value "1".

$$HTCI = HTC \div HTD_{HOSPITAL} \quad (16)$$

Once the HTCI is evaluated, it is possible to estimate the Hospital Performance Index (HPI) which is defined as a linear combination between the numerical values given by the capacity of the hospital to treat and its intrinsic security (IS), see equation 17.

$$HPI = [(HTCI \times \eta) + (IS \times \theta)] \div (\eta + \theta) \quad (17)$$

Where the coefficients η and θ depend on the hospital type as follows:

- City Hospital: $\eta = 3$ and $\theta = 2$;
- Country Hospital: $\eta = 2$ and $\theta = 3$;
- Small City Hospital: $\eta = 2$ and $\theta = 2$.

The meaning of assigning different values for the coefficients η and θ is related to the specific context where the hospital is situated, which can be more important for strategic functions (city hospital) than hosting purposes of the facility (country hospital) or the other way around. Usually country hospitals are built with the aim to serve many different surrounding villages and are located in an intermediate position easy to reach by the most of the villages themselves. During an earthquake, road viability can be interrupted and the injured people locally treated by field medical installation or aerial evacuated to other hospitals in the safe areas as the strategic function of this hospital type is not really important. Moreover, by considering the high concentration in one facility of hospital patients (coming from the villages), the risk of structural collapse which could make hospital as the most numerous point of severe injured people must be avoided. For this reason, the hosting function of this hospital type must be predominant than the strategic one. For small city hospitals, the η and θ values define a "middle scenario" where any specific function of the health structure is considered predominant to the other.

4. Seismic Risk Mtitgation

4.1. Response and Prevention

According to the risk management chain, the risk treatment part applied to the hospital case study takes into consideration two main areas of intervention according to the effects on the disaster cycle phases, which are in this specific dissertation the prevention and the response.

In the following chapter the terminology used tends to underline more the type of intervention instead of the phase of the expected effects. The defined measures are classified in:

- direct interventions: include all those measures to be carried out directly to the hospital system;
- indirect interventions: include all those actions on other systems involved in the medical response chain.

Although this light difference in the approach, it is clear how the direct interventions can be linked to the preventions phase while the indirect ones belong to the coping phase during disasters. Finally, a cost analysis is carried out according to the *actions type*.

4.2. Direct Actions

According to the direct measures on the hospital system, four different types of actions have been defined:

- Type 1: interventions on emergency planning and organizational aspects;
- Type 2: actions on medical equipment and architectural elements;
- Type 3: measures on basic installations;
- Type 4: actions on medical personnel;
- Type 5: structural retrofitting.

Type 1

The actions involved in this category are supposed to make part of the ordinary activity of the hospital and they include the development of emergency plans for seismic risk (in this specific case) and the management of emergency department overcrowding scenario, besides the periodic organization of drills and evacuation simulation. In addition this type of interventions includes the change of destination of use of existing hospital areas such as the goal of empowering the surgical capacity. Type 1 actions can be limited to the hospital scale or including the whole participants to the medical response chain.

Type 2

Many references [22, 23] suggest proper non-structural components anchorage and fixing for hospitals. For instance, figure 4.1 reports a specific form from the California Building Code (CBC 2010) with the definition of specific seismic measures which can be carried out for equipment and basic installation anchorage and fixing [78]. The seismic certification of non-structural components is already present in the IBC 2009 Section 1708.4 [79] which is the base for the CBC 2010 section 1708A.4 while the special certification for designated seismic systems is contained in the ASCE 7-05 section 13.2.2 [80]. Moreover, in the CBC 2010 Section 1708A.4.1 are listed the components and equipment which need to comply with the specific seismic certification:

1. Emergency and standby power systems;
2. Elevator equipment (excluding elevator cabs);
3. Components with hazardous contents;
4. Smoke control fans;
5. Exhaust fans;
6. Switchgear;
7. Motor control centers;
8. X-Ray machines in fluoroscopy rooms;
9. CT (Computerized Tomography) Scanners;
10. Air conditioning units;
11. Air handling units;
12. Chillers;
13. Cooling Towers;
14. Transformers;
15. Electrical substations;
16. UPS and batteries;
17. Distribution panels;
18. Control panels.

The following components are exempt from special seismic certification:

1. Equipment and components installed in non-conforming buildings;

2. Equipment and components weighting not more than 20lbs and supported directly on structures (not mounted on other equipment or components).

Emergency plans development are considered at null cost for the structure while the medical equipment and architectural elements fixing is considered the cheapest mitigation action to be carried out in a health structure.

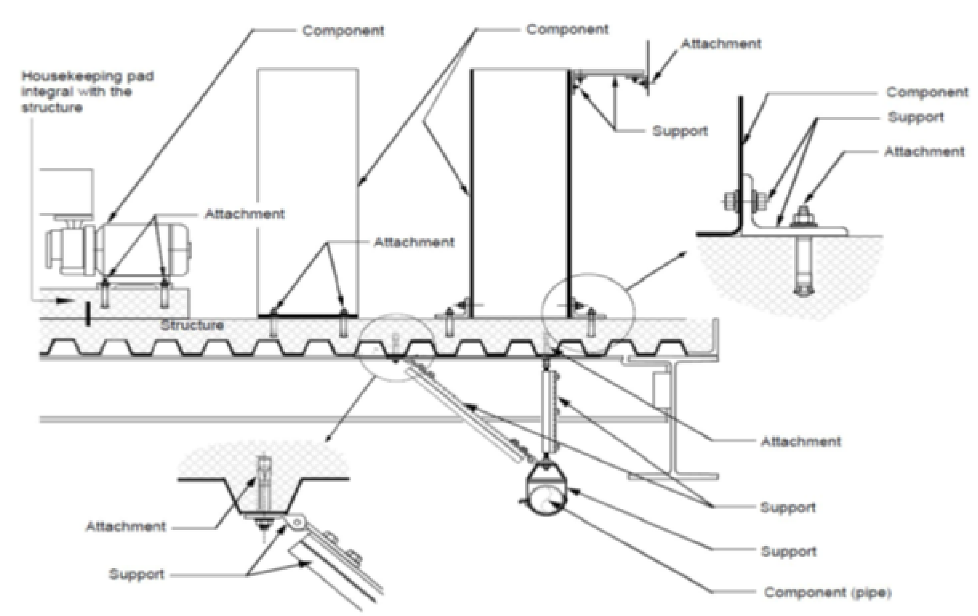

Figure 4.1.: Approved equipment anchorage in CBC 2010.

Type 3

The basic installation related actions regard the systems' elements anchorage, the safe storage of some essential and dangerous elements (as GPL cylinders for the back-up generator or medical gas cylinders), the use of flexible pipes and connections for the medical gas and plumbing system pipes and building redundant systems. Flexible connections are suggested for reducing the seismic risk, see figure 4.2, especially when passing from one building to an other one and for those life support related systems such as power system and medical gas. Furthermore, special attention should be given to those pipes containing inflammables such as the oil supply for back-up generator.

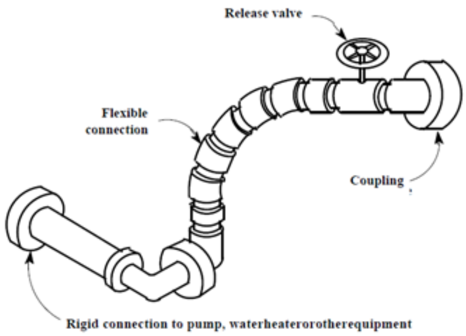

Figure 4.2.: Example of flexible connection.

Regarding the anchorage of the basic installations and architectonics elements, table 4.1 reports which non-structural elements have to be considered in the seismic risk mitigation [22].

Architectural	Equipments & Furnishings	Basic Installations and Services
• Divisions and partitions	• Medical equipment	• Medical gases
• Interiors	• Industrial equipment	• Industrial fuel
• Facades	• Office Equipment	• Electricity
• False Ceilings	• Furnishings	• Telecommunications
• Covering elements	• Supplies	• Vaccum network
• Cornices	• Clinical Files	• Drinking water
• Terraces	• Pharmacy shelving	• Industrial water
• Chimneys		• Air conditioning
• Surfacing		• Steam
• Glass		• Piping
• Attachments (Signs, etc.)		• Waste disposal
• Ceilings		
• Antennas		

Table 4.1.: Anchorage of non-structural elements [22].

Type 4

Type 4 takes into account the personnel related actions such as the assumption of new medical resources.

Type 5

Type 5 interventions include the structural retrofitting on the building such as the substitution of a heavy tile roof, which is more susceptible to movement during an earthquake, by a lighter and safer roof and/or reinforcement and strengthening of walls by covering their surfaces with wire mesh and filling with cement.

4.3. Indirect Actions

With the term “indirect actions” is intended all that group of interventions involving other institutions and resources involved in the medical response chain supporting the health structures. In this dissertation they include field hospitals (figure 4.3a) or more in general mobile medical clinics (figure 4.3b) which are managed by the local or national civil protection offices or by NGOs and institutional rescuing association such as the Red Cross.

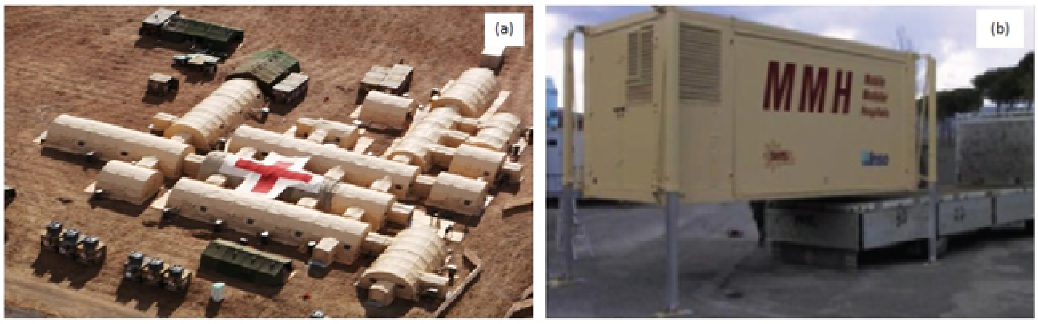

Figure 4.3.: (a)Example of field hospital [81]; (b)Example of mobile medical shelter [82].

Moreover, other indirect intervention regard the medical evacuation by air to other structures, see figure 4.4. For instance in case of the L’Aquila earthquake (Italy, 2009) all the indirect interventions above have been largely used in the aftermath of the earthquake for the management of the acute care medical response “*Within 24 hours it was completely replaced by the first of two field hospitals that arrived in the area. Meanwhile, early management of casualties was largely in the hands of the Italian armed forces, which employed "Medevac" aerial evacuation techniques to remove seriously injured patients to hospitals outside the disaster area* [83]”.

Figure 4.4.: Example of Medevac.

As summary, the following types of indirect interventions have been analyzed:

- Type 1: mobile medical unit installation;
- Type 2: medical aerial evacuation of casualties to hospitals outside the disaster area.

4.4. Cost Assessment

4.4.1. Overview

The estimated costs depend on the specific intervention since for each retrofitting type different material, personnel and duration are involved. Following is presented a cost analysis including the single cost per type of intervention and category: direct and indirect measures.

4.4.2. Cost Analysis of Direct Actions

According to the literature [84-89] and subsequent validation by experts' opinion, the economic costs are reported below. For type 1 interventions, it was chosen to consider those actions free cost for the hospital since they belong to the ordinary activity of facility or institutional staff. Moreover type 2 and type 3 were considered on a same specific cost category since despite of different targets, the interventions are considered the same for both types.

- Concerning type 2 and type 3 retrofitting, the succeeding cost estimations can be defined as follows:
  - Anchorage of medical equipment: 150 €/equipment;
  - Elevators securing, anchorage of water and medical gas systems' pipes, back up generators and medical gas tanks: 2.5 €/m^2.
- For type 4 actions, they have been considered both the cost of the additional personnel to cover the operating theatres H24 and 7/7 (180.000€/year including 1 surgeon and 1 anaesthetist) and the cost necessary for changing the destination of use of a specific hospital area which includes the acquisition of specific medical equipment (340.000€/surgery table, see table below [92]) and the installation of specific lifeline systems [93, 94] (350.000€/table surgery[95]). Please note that all costs refer to a single operating table.
- Type 5: with regards to the structural measures, the total costs are estimated around 200€/m^{2}which include following specific actions:
  - Intervention with reinforced concrete partitions;
  - Intervention with dissipative bracings;

- Horizontal structures;
- Vertical structures;
- Foundations;
- Intervention of basic insulation.

MEDICAL EQUIPMET	COST (€)
ANAESTHETIC EQUIPEMENT	25.000
AUTOCLAVE	5.000
AUTOTRANSFUSION SYSTEM	1.000*
EXTERNAL PACEMAKER	3.000
ENDOSCOPE SSUPPORTING SYSTEM	15.000
ENDOSCOPE	20.000
LABORATORY FREEZER	3.000
AORTIC BALLOON PUMP	35.000
DEFIBRILLATOR	10.000
ECOTOMOGRAPH -	20.000
FIBROSCOPE FOR INTUBATION	5.000
SCIALITIC LAMP	10.000
MONITOR	10.000
SYRINGE PUMP	1.000*
BIOLOGICAL REFRIDGERATOR	2.500
PULSOXIMETER	1.000*
STERNOTOME	25.000
ELECTROSURGICAL SCALPEL	25.000
SURGICAL TABLE	50.000
TOTAL	264.000

*Annual cost according to the service/rental contracts.

Table 4.2.: Cost estimation of the technology dotation in surgery room.

The lifeline and structural costs for installing a surgery room, within an already existing area in the hospital, are estimated by the necessity to guarantee functional efficiency and safety. For this reason operating rooms require special systems which are designed for providing the permanent continuity of medical gases, thermal comfort and power distribution. Moreover, air system is essential for surgery room hygiene (protective against postoperative infections). Electrical safety requires all the technical features to avoid micro shock and power disruptions [93] while the presence of separated paths of dirty and clean areas is essential. Particular attention is also given to specific procedures and disposals for special waste, see table 4.3.

NON STRUCTURAL ASPECTS FOR SURGERY ROOM DESIGN
MEDICAL GAS SYTEM
VCCC
ELECTRICAL
SUPPORTING AREAS (ANESTHESIA AND WAKING UP)
CLEAN – DIRTY PATHS SEPARATION
SPECIAL GARBAGE PATH
350.000 € / surgery table

Table 4.3.: Non-structural aspects for surgery room installation.

4.4.3. Cost Analysis of Indirect Actions

The economic evaluation of in direct methods involves both the estimated costs of air-transporting the patient to an other facility and those related to transportation and installation of mobile medical units (shelter or tent). In particular, the choice of considering air-transportation was taken into consideration because the road viability conditions may not be practicable in aftermath of an earthquake. The cost evaluation is analyzed as follows:

- Type 1: the cost of installing a mobile medical unit for field surgical treatment per surgical table is estimated according to the type of unit: tent or shelter. The cost of installing a shelter as mobile medical unit is around 415.000€ which includes the cost of the shelter (150.000€), the acquisition of medical devices (264.000€) and the transportation (2€/km) [91]. A tent unit costs around 223.000€ which is 9.000€ for the tent and 214.000€ for the medical instrumentation acquisition. The lower cost of the instrumentation for tent depends to the fact that a tent does not permit the installation of all equipment available in a real operating room (or shelter) for poor technical and structural standards.
- Type 2: medical aerial evacuation of casualties to hospitals outside the disaster area. According to [90] a single evacuation costs around 5.000€ per patient.

It is important to remind how the analysis assumes only the coping phase. The additional costs deriving from the casualties' hospitalization have not been taken into consideration in this cost assessment.

Part II.

RESULTS

5. Risk Assessment - Italian Case Study (OSMA)

The following chapter reports the application of the risk assessment methodology described in the previous chapters. The methodology has been tested to the Italian context which consists of the OSMA hospital in Florence. The seismic scenario is given by the 1919 Mugello earthquake which takes into consideration a seismic magnitude I=6.

5.1. OSMA Hospital Description

The OSMA hospital (Ospedale di Santissima Maria Annunziata) is a Florentine public health structure providing three hundred hospital beds and six operating theatres. The hospital is situated at the south of Florence. Moreover, hospital accessibility is available 24hours per day and besides the ordinary road access there is a helicopter airstrip for the aerial transportation of casualties, see figure 5.1.

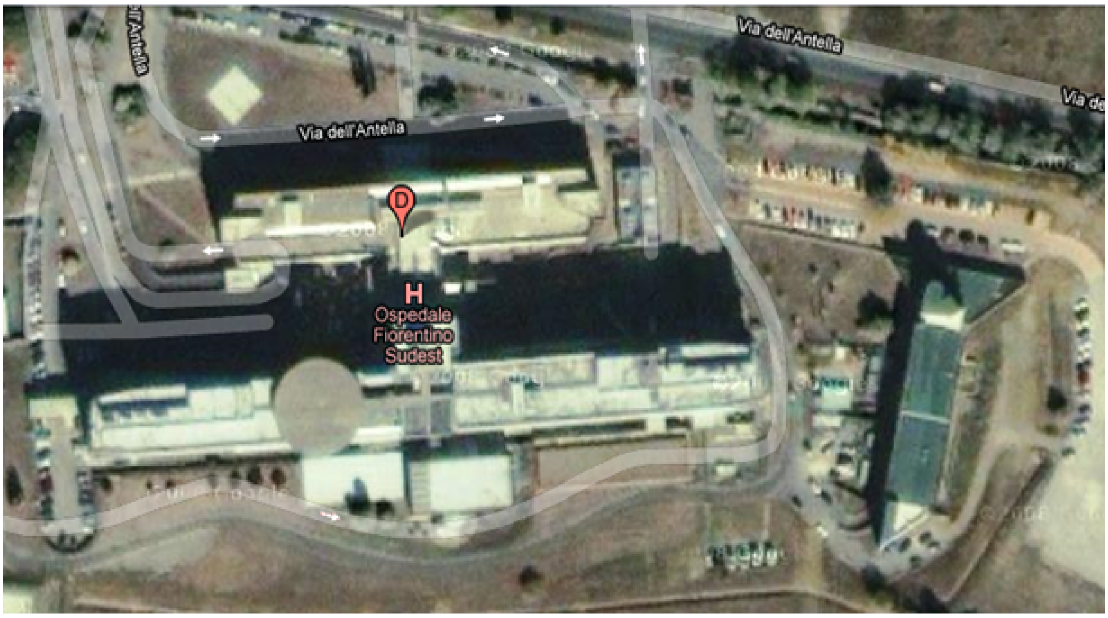

Figure 5.1.: OSMA hospital in Florence, Italy - [source: Googlemap].

As reported in figure 5.2, the Florence OSMA hospital is divided in three main buildings which are “building 1a (Lotto1)”, ”building 1c (Lotto2)” and the “corridor 1b (Collegamento).”

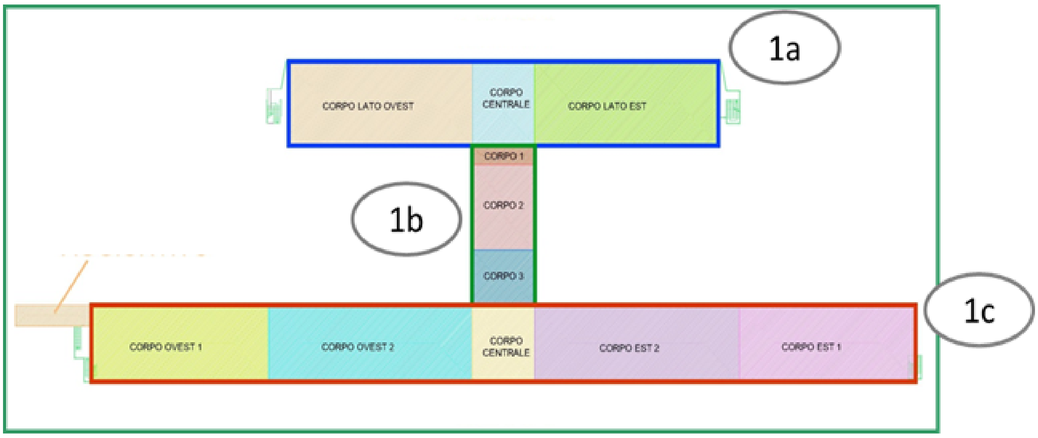

Figure 5.2.: OSMA hospital plant [Source: Florence Health System Technical Dept.].

5.2. Seismic Vulnerability Assessment

According to the rapid evaluation forms described in chapter 2.1, the results are presented in tables 5.1 and 5.2 by considering a seismic intensity I=6. Each building provides with a vulnerability estimation according to the different vulnerability grades: Low (L), Medium (M) and High (H).

I=6		VULNERABILITY			
		Structural	Non Structural		
N.	Name		architect	Equipment&Furnishing	basic installations
1A	Lotto 1	L	M	M	M
1B	Collegamento	L	M	M	M
1C	Lotto 2	L	M	M	M

Table 5.1.: Results of the structural and non-structural vulnerability assessments at the OSMA hospital.

I=6		VULNERABILITY		BEDS	
		Administartaive/organizational		OT	Hospital and ICU beds
N.	Name	Capability*	Services distribution**		
1A	Lotto 1	M	L		130 (HB)
1B	Collegamento	M	L		
1C	Lotto 2	M	L	6	191 (HB) + 10 (ICU)

Table 5.2.: Results of the administrative/organizational vulnerability assessment at the OSMA hospital.

Besides the administrative/organizational vulnerability, table 5.2 reports the number of ordinary hospital beds belonging to Intensive Care Unit (ICU) and the number of the operating tables. Both building 1A and 1C contain hospital beds (HB) while operating tables (OT) and ICU beds are located in building 1C only.

Regarding the Leontief model application, five experts were interviewed for the definition of the matrix coefficients and they included:

- 2 hospital engineers;
- 1 technical director;
- 1 physician;
- 1 health medical director.

The questionnaire consisted of 256 semi-structured questions and considered both expertise and confidence levels. The expertise weighting range has been defined as follows:

- technical director =1;
- medical director = 0.75;
- hospital engineer = 0.5;
- hospital physician = 0.3.

While for the confidence levels on the requested opinion:

- strongly agree: =1;
- more agree than disagree = 0.95;
- no opinion = 0.90;
- more disagree than agree = 0.85.
- strongly disagree = 0.80.

Finally for the single values which compose the single expert's matrix coefficients, five values have been defined as follows:

- complete stoppage: =1;
- strong impact = 0.95;
- some evident effects = 0.90;
- negligible effects = 0.85;
- no effects = 0.80.

Figure 5.3 reports a view of the developed electronic check list used during the interviews.

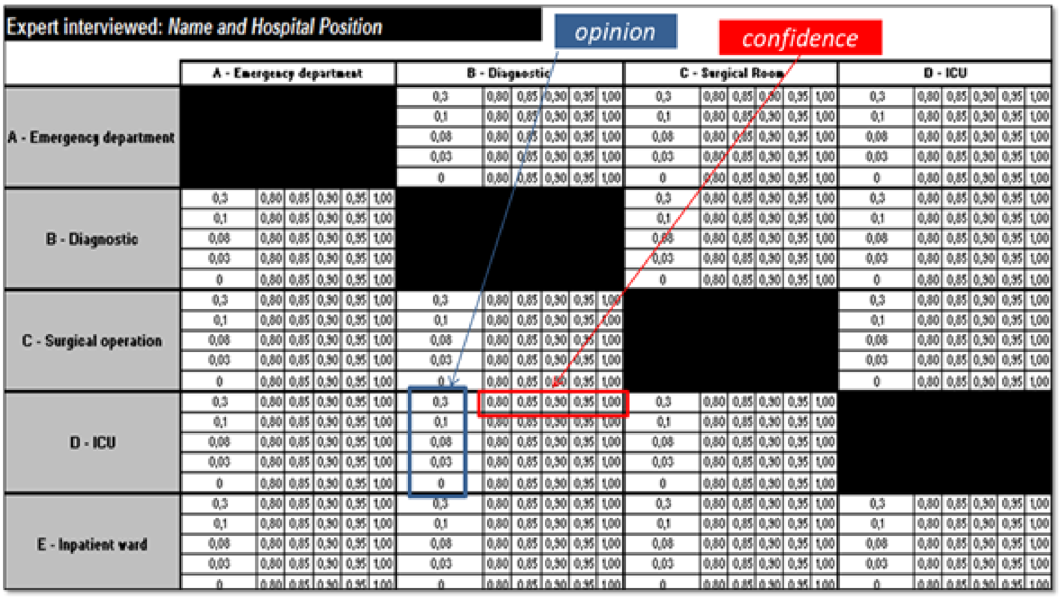

Figure 5.3.: Electronic check list used during the interviews to the experts.

With regards to the validation phase, this was carried out by considering both the experts' and the opinions' reliability. The results are shown in figure 5.4 and 5.5 respectively. All the experts are within the 0.05 confidence range and only three opinions of 256 are out of the range 0.05.

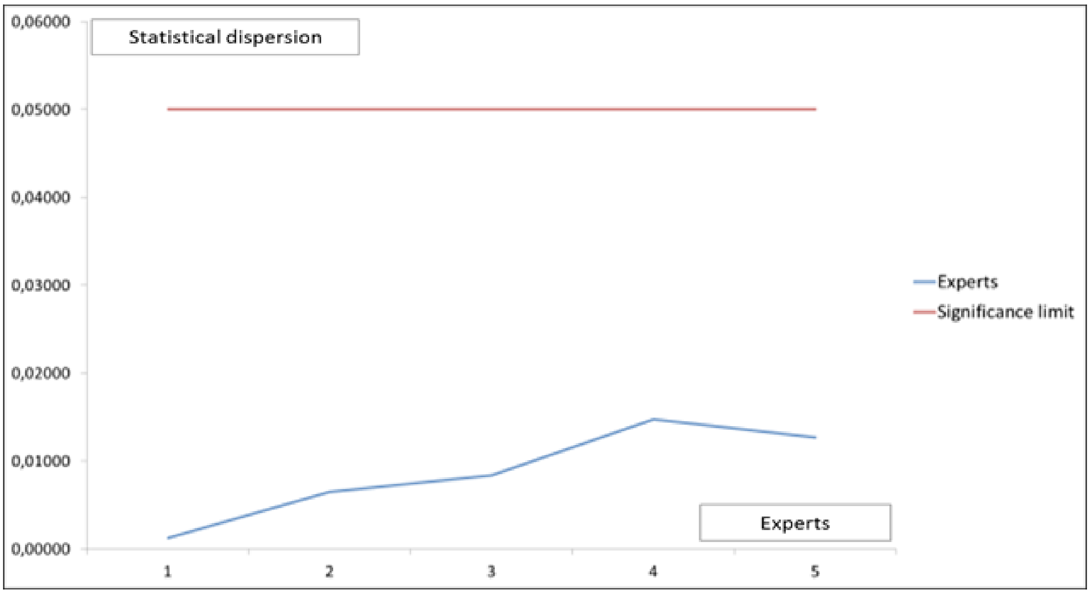

Figure 5.4.: Experts' evaluation t-test.

The opinions showing a statistical difference belong to the following scenarios:

- the diagnostic area impacting the crisis unit (0.053);
- the crisis unit area impacting the internal viability (0.053);
- the fire system impacting the hospital accessibility(0.051).

In spite of exceeding of statistical threshold, all the values were accepted in the Leontief matrix coefficients ‘A’ as valid values since the approximated two decimal values coincide with the limit value.

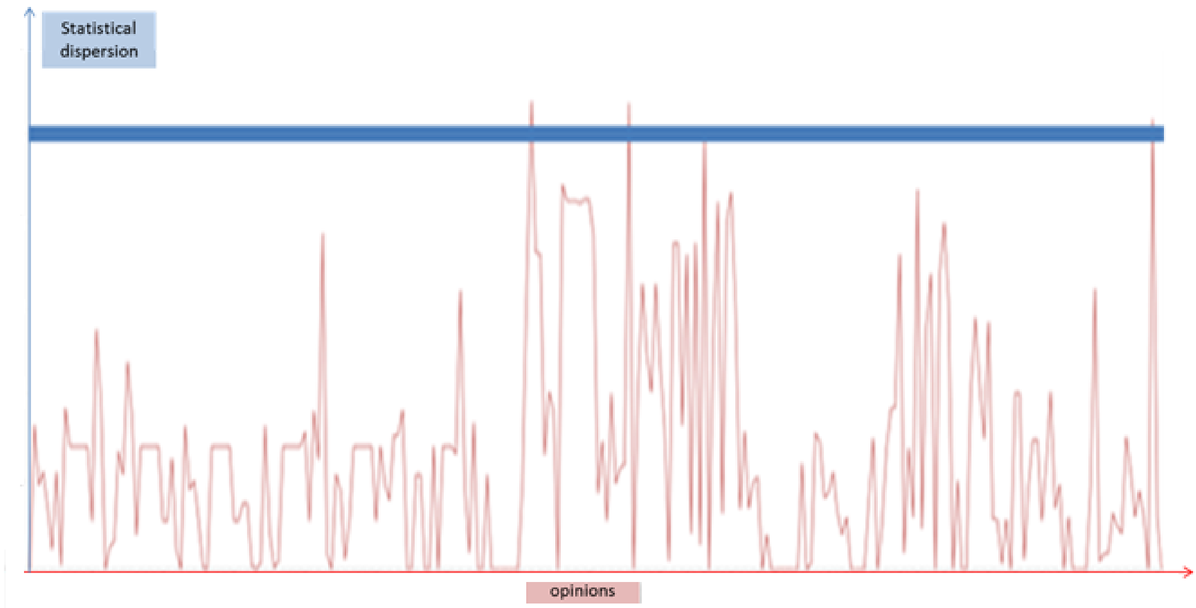

Figure 5.5.: Opinions’ statistical evaluation test.

Finally the highest dependency index ‘δ’ belongs to the surgical area with a value of 2.05 while the highest gain index ‘ρ’ belongs to the power system with a value of 2.729. In figure 5.6 the output vector concerning the inoperability level of each hospital area is reported, obtained as combination between the implemented Leontief matrix and the seismic intensity I=6 perturbation introduced by the input inoperability vector evaluated with the rapid vulnerability assessment forms.

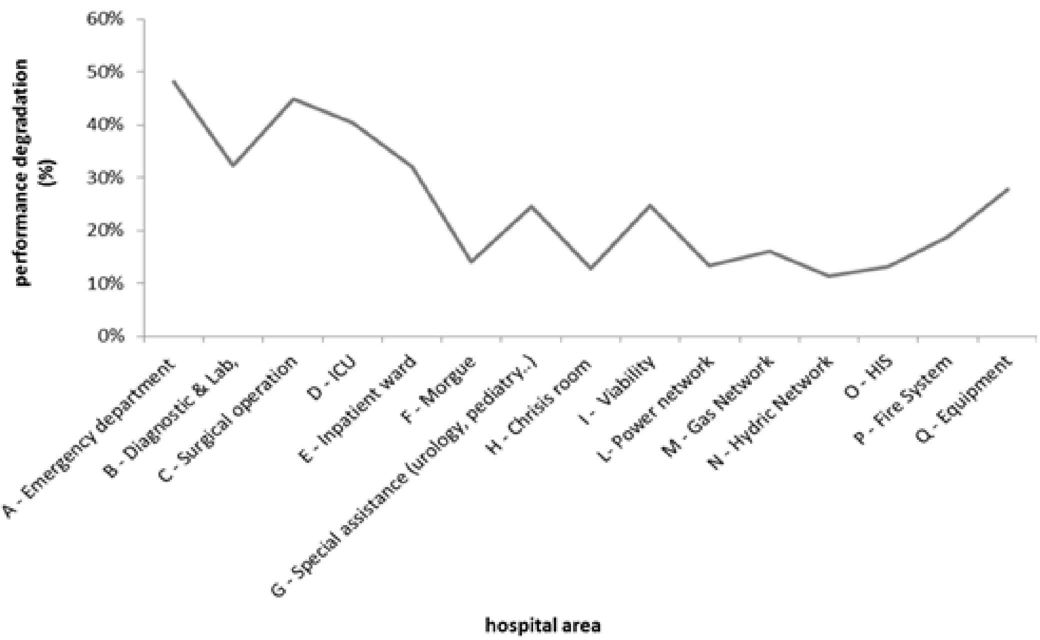

Figure 5.6.: Hospital area degradation according to a seismic intensity I=6.

Big differences exist amongst hospital areas: Emergency department, Diagnostic, Operating theatre, ICU and Impatient awards are the most affected areas during earthquakes. Plumbing system is the least affected area. With regards to the development of the FTA model for OSMA hospital, figure 5.7, 5.8 and 5.9 report the graphic models for the surgery, ICU and hospital beds area respectively.

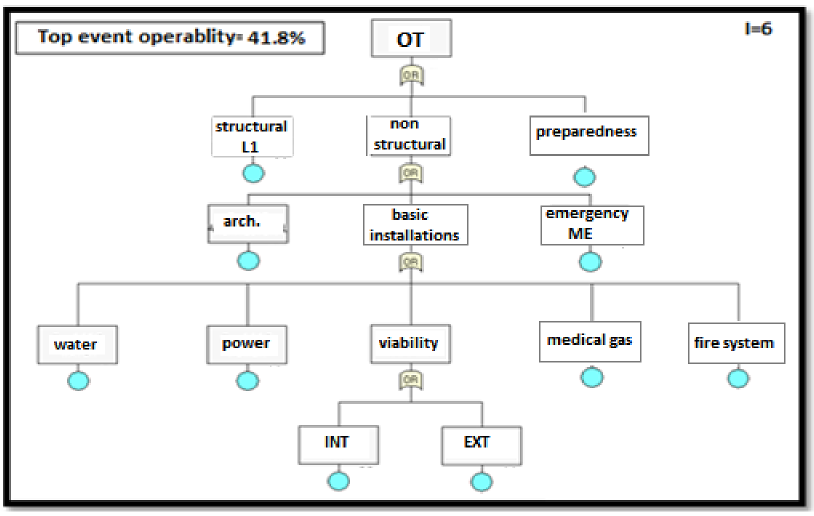

Figure 5.7.: Surgery area at the OSMA hospital described by the FTA model according to a seismic intensity I=6.

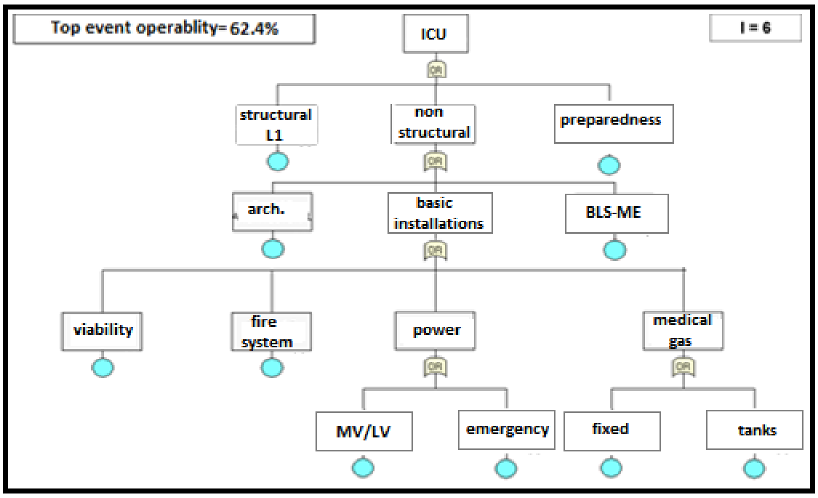

Figure 5.8.: ICU area at the OSMA hospital described by the FTA model according to a seismic intensity I=6.

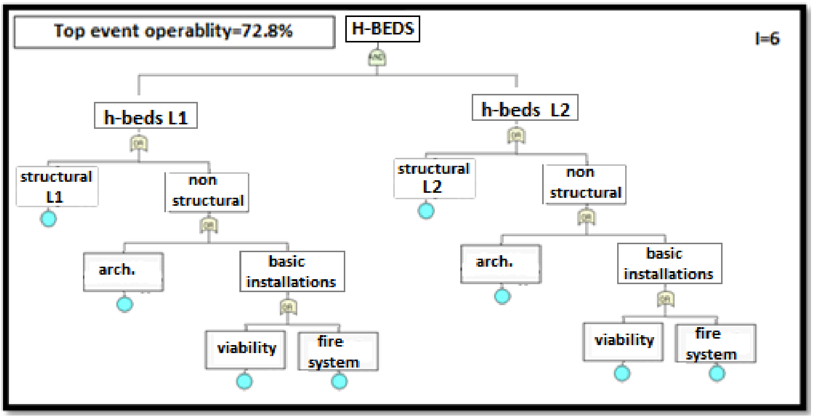

Figure 5.9.: Hospital beds at the OSMA hospital described by the FTA model according to a seismic intensity I=6.

The top event operability according to the specific medical area is as follows: 41.8% for the operating theatre, 62.4% for the ICU and 72.8% for the hospital beds area. Moreover, the hospital beds area is the only destination of use which depends on both the building 1A and 1C and according to the non-structural elements, only the fire system, the internal viability and the architectural components are taken into consideration. The surgical room fault tree differs from the ICU tree for two main elements, the presence of the water system (essential only in the surgery room) and the medical equipment contribution which consists of the emergency medical care in the operating theatre and the life support ones in the ICU area.

5.3. Performance Assessment

According to the seismic intensity scenario I=6, figure 5.10 reports the performance degradations of the hospital system according to the specific medical area and to the type of model applied: the Leontief and Fault Tree Analysis (FTA).

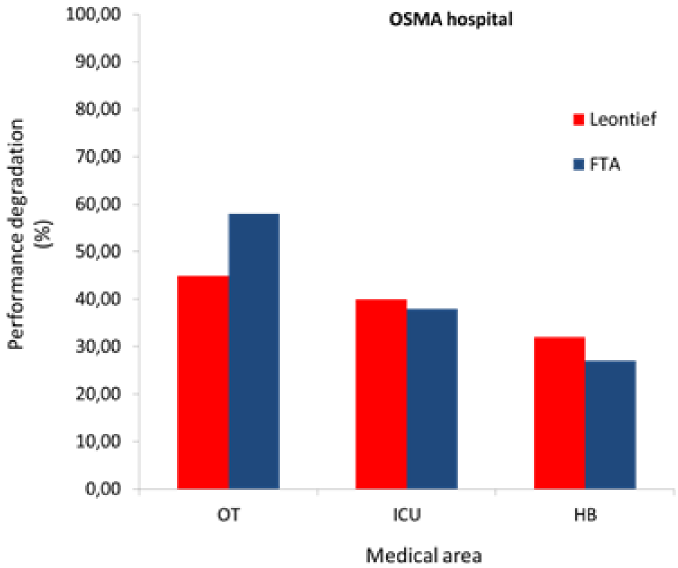

Figure 5.10.: Performance degradation according to both medical area and model type at OSMA hospital (I=6).

Figure 5.11a and 5.11b show respectively the estimated “HTC” and “IS” indices resulting from the application of Leontief and FTA models. Moreover, two different temporal scenarios are evaluated in the analysis: the day and night/holidays scenarios.

The HTC degradation between day and night is very different for both models (one order of difference). By analyzing the different response according to the type of used model, the HTC degradation estimated by FTA is higher than the one assessed by Leontief (58% to 45% during the day and 96% to 94% in the night time), while the IS index estimated by Leontief is higher than the FTA one (30% to 25%). For both models, no significant differences are assessed for the IS values according to the day or time scenarios.

In order to better analyze and understand the differences resulting from the application of the two models, in the next paragraph a sensitivity analysis on both the specific medical areas and the hospital performance indicators is carried out and takes into consideration the seismic intensity range I=4-10.

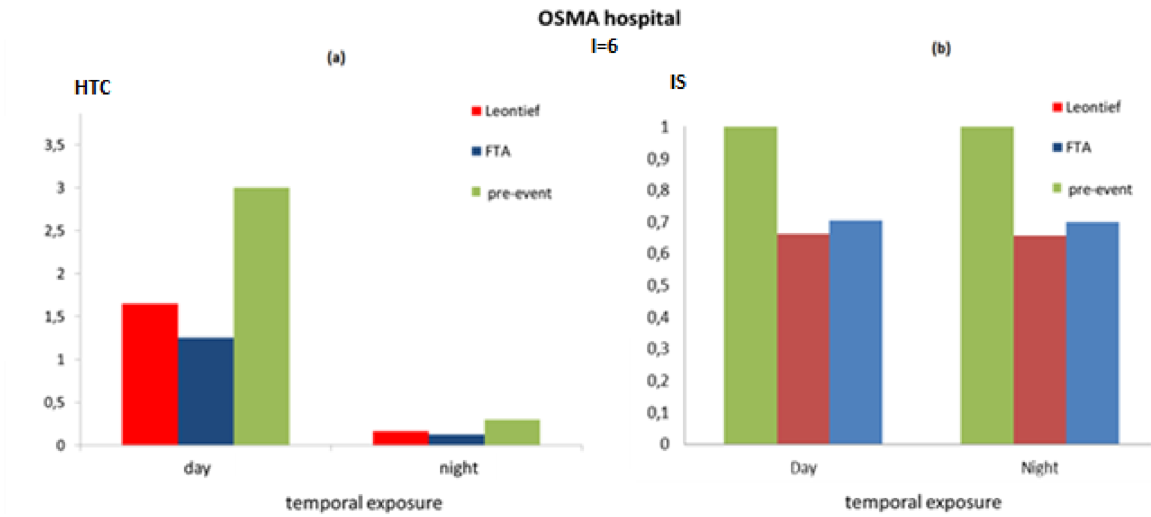

Figure 5.11.: Hospital performance indices degradation according to medical area and model type (I=6).

5.3.1. Sensitivity Analysis on System and Performance Degradation

Hospital area

From the Leontief model application it is possible to analyze the seismic impact on the single medical or technical area within the OSMA hospital in the seismic intensity range I=4-10.

As reported in figure 5.12, it is possible to individuate three different groups of areas. The first one consists of those areas which remain below the 50% inoperability at any seismic intensity such as internal connection, gas network, fire system and hydric network, the second group is composed by those medical areas staying between 50% and 100% degradation at the high seismic intensities (I=8-10) such as the power system, the in-patient ward and the medical areas which provide special cares. Finally the third group formed by the most vulnerable areas (100% degradation at the high intensities I=8-10) which includes the emergency department, the surgery, imaging and ICU areas.

The seismic behavior show high differences to the high intensities while for the low intensities the hospital areas' degradation is almost similar. The emergency dept., diagnostic, operating theatre, ICU are the most affected areas in hospital during earthquakes. The results of FTA application, the results are reported in figure 5.13 where the levels of degradation are shown for surgery, ICU and hospital beds.

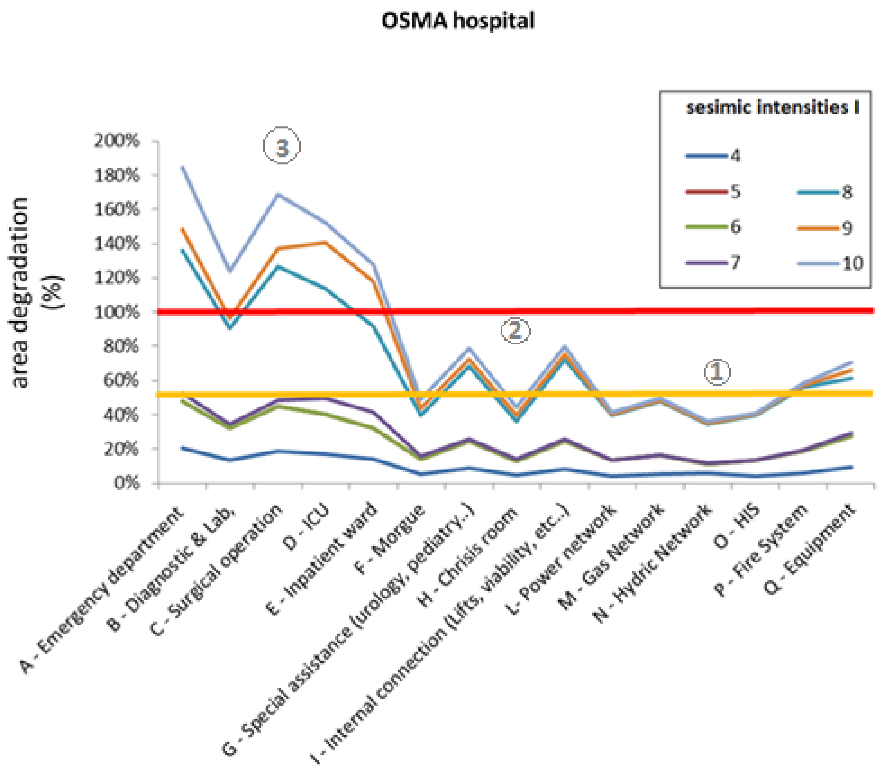

Figure 5.12.: Seismic sensitivity analysis by considering the level of degradation of each medical area at the OSMA.

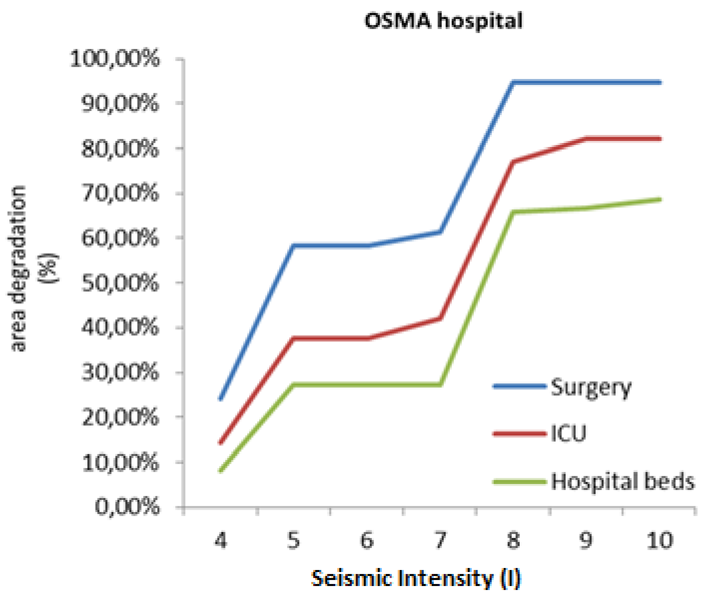

Figure 5.13.: Medical areas degradation assessed by the FTA model application to OSMA Hospital (Italy).

The seismic behavior is characterized by three main areas according to the system degradation. Frist the null-degradation zone for I=0-4, the second one involves the medium-high intensities I=5-7 and shows degradation between 30-60%, (increasing from the hospital beds, to the ICU and to OT respectively). The third area includes the high seismic intensities I=8-10 and yields hospital area degradations between 70%-100%.

Moreover, I=5 and I= 8 represent the breaking points of the previous areas. Big differences exist between surgery, ICU and hospital beds areas: surgery is the most affected area (60% degradation already at I=5 and almost 100% at I=8), ICU passes the 50% degradation only at I >7 with a maximum degradation level estimated around 80% and finally the hospital beds area which is below 60% for I=6 and with a 70% degradation as maximum level for I=10.

In figure 5.14 is reported the comparison between Leontief and FTA models. The FTA model shows a stronger stability than the Leontief one especially for the high seismic intensities (I>7). For lower intensities (I<7) both models have similar trends, with the following differences: surgery area degradation is stronger for FTA model than Leontief while ICU and bed hospitals (BH) show lower degradation with FTA than Leontief.

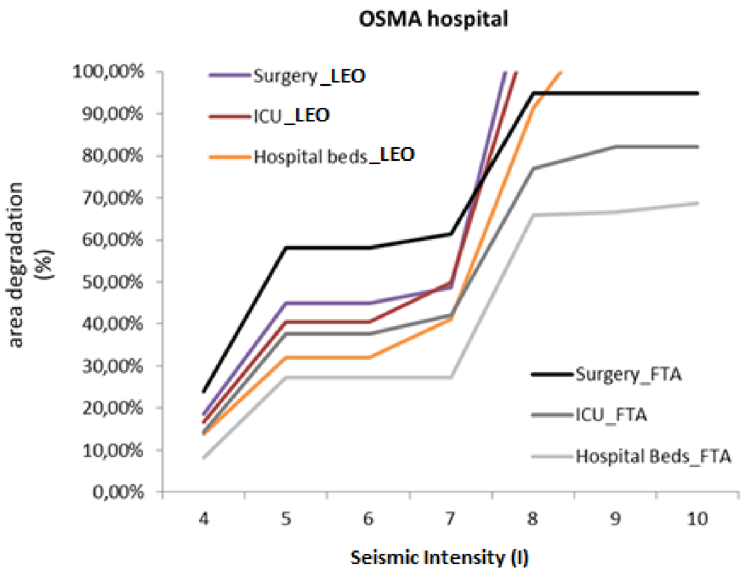

Figure 5.14.: FTA-LEONTIEF model comparison at OSMA Hospital.

Hospital performance

With regards to the OSMA case study, figure 5.15a shows the HTC index estimated by FTA for the different seismic intensities. The blue line shows the HTC trend during the daytime while the red line is for the HTC during the night time and holidays. Big differences exist between the night and day time. For instance, considering a seismic intensity of I=4, the night HTC is 0.23 and presents a value ten times lower than the day one which is 2.3. Night time and holidays HTC has a linear trend with the seismic intensity I=8 as critical breaking point to which corresponds an almost null HTC. Even if the trend for the day time HTC is steeper, I=8 represents the critical breaking point also for the daytime with a HTC estimation of 0.25 which corresponds to a 94.8% degradation from the pre-event status. For I>=8 both indexes (day and night/holidays scenarios) present close values. Figure 5.15b reports the HTC analysis for the different seismic levels carried out with Leontief. The blue line shows the HTC trend during day while the red line belongs to HTC during night time and holidays. Also the FTA model gives big differences between the night and day time HTC for intensity values I<8. While for I>8 the Leontief system is not stable anymore. For FTA, night time and holidays HTC has a more constant trend while for the day time HTC the trend decreases steeply.

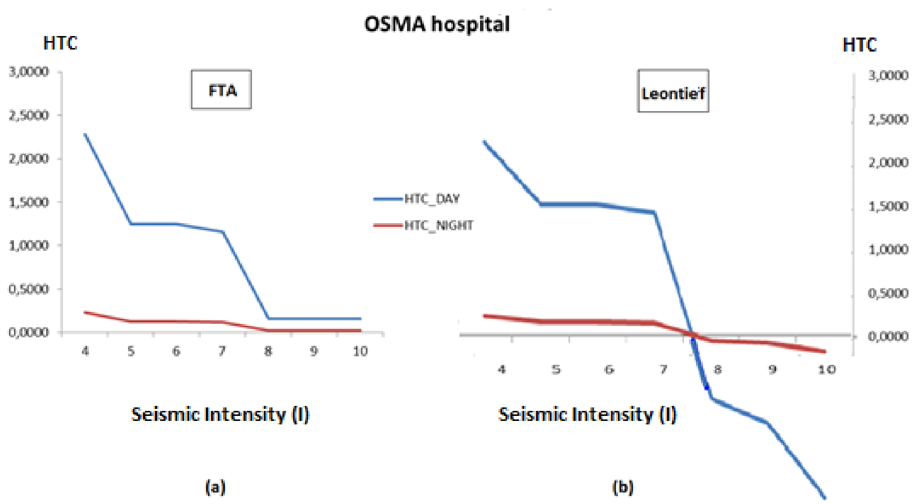

Figure 5.15.: OSMA hospital (Italy) HTC estimation with: (a)FTA model and (b)Leontief model.

Finally, figure 5.16 reports the comparisons between HTC trends evaluated by Leontief and FTA models in the same graph. The night time and holidays HTC trend has similar behavior in both models until the seismic intensity I=7. For the day time HTC trend, even if the FTA model estimates lower values than Leontief, both models show similar trends for the seismic range I=4-7. Over 7, Leontief is not stable any more while FTA decreases slowly to the value “zero”.

According to the index (IS) at the different seismic intensities, figure 5.17a reports the analysis estimated by the FTA model. The blue line shows the HTC trend during day while the red line belongs to HTC during night time and holidays scenario. No appreciable differences exist between the night/holidays and the day time scenarios. Both trends have a steep linear trend with two main breaking points: the first one at the seismic level I=5 with a IS degradation of 50% (in relation to the pre-event IS=1) and the second one at I=8 with a 70% degradation. Figure 5.17b reports the IS analysis carried out with the Leontief model. Blue line shows the HTC trend during day while red line belongs to HTC during night time and holidays scenarios. Similare to the FTA analysis, no appreciable differences are evaluated between the night and day trends. The analysis with Leontief model is only valid for intensities lower than I=8 because for higher values the system is not stable anymore.

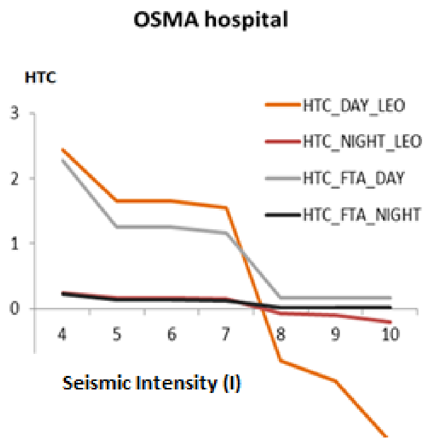

Figure 5.16.: FTA and Leontief HTCs comparison at the OSMA hospital.

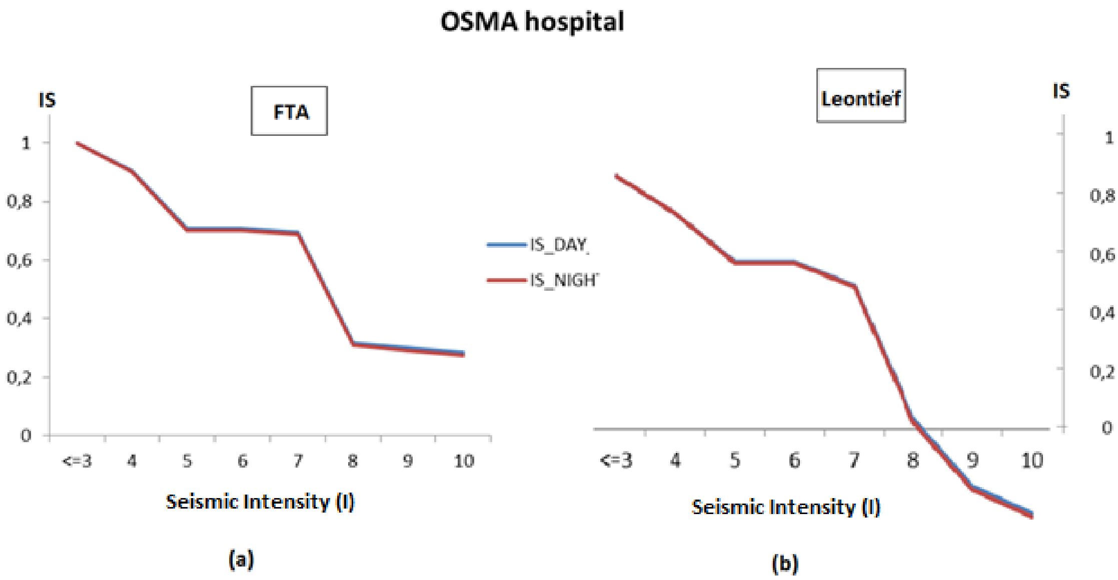

Figure 5.17.: OSMA hospital (Italy) HTC estimation with: (a)FTA model and (b)Leontief model.

As described for the HTC comparison, figure 5.18 shows in one graph the IS trends evaluated with Leontief and FTA models. As already described above, both models produce similar outcomes in the seismic range (I=1-7) while for I=8, the Leontief results are not reliable because of the system instability.

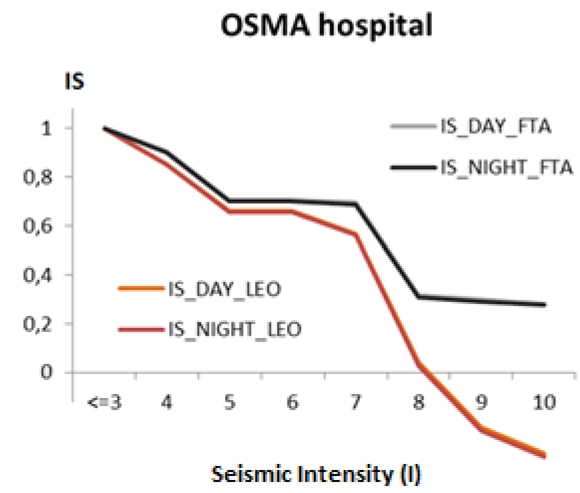

Figure 5.18.: FTA and Leontief IS indices comparison at the OSMA hospital.

5.4. Response Assessment

Florence is the main city in Tuscany and it is surrounded by a seismic country area. In order to build a reliable scenario for this case study, the 1919 Mugello earthquake has been considered in terms of geological and seismic features. In addition a field work has been carried out to adapt the past seismic event to the current scenario [96]. The last major seismic disaster in Tuscany was the earthquake of 29 June 1919, whose epicentre was close to the town of Vicchio in the Mugello (the mountains about 30 km north of Florence). The estimated intensity was 6.2 and the intensity reached level X on the Mercalli scale used at the time. It was the worst earthquake in Mugello area since 1542 [97].

These data have been processed by SIGE, a numerical simulation software developed by the Italian Civil Protection Department. The software applies the past seismic conditions to the actual situation such as the age of buildings, type of structures and current resident population [98]. Following are the data obtained by the numerical simulation: 390 red and yellow triaged patients (T1+T2), 1950 green triaged patients and 260 deaths. Hence, by applying equation (14) the Florence HTD is 130 patients which represent the total medical demand in Florence due to the seismic event (I=6).

By considering the equation (15) in chapter 3, every single hospital of the five composing the health system in Florence should face with a $HTD_{HOSPITAL}$ equal to 2.6 patients/h in the acute response within the first ten hours. Indeed, with regards to the HTCI evaluation, the seismic intensity I=6 permits to calculate the values as reported in table 5.3 according to both night and day time scenarios.

HTC				HTCI			
FTA		LEONTIEF		FTA		LEONTIEF	
DAY	NIGHT	DAY	NIGHT	DAY	NIGHT	DAY	NIGHT
1.25	0.13	1.65	0.17	0.48	0.05	0.64	0.06

Table 5.3.: HTC and HTCI values determined for the OSMA hospital at a seismic intensity I=6.

Given the fact that for a seismic intensity I=6 the Leontief model is still in the stable range, outputs from both FTA and Leontief models are considered. Table 5.3 shows how the day time HTCI evaluated by FTA model is a bit lower than the one estimated by Leontief. Both values present a day HTCI of around 0.5. As reported in figure 5.19, the estimated HTCI value means that only half of the whole medical demand can be satisfied in aftermath of a I=6 earthquake during the day time. For the night time scenario, no appreciable differences exist between the models and according to the calculated HTCI it would be able to satisfy only 5% of the whole medical treatment demand. A HTCI=1 would be the target value representing the scenario where the whole hospital demand from the local population is satisfied by the hospital treatment capacity.

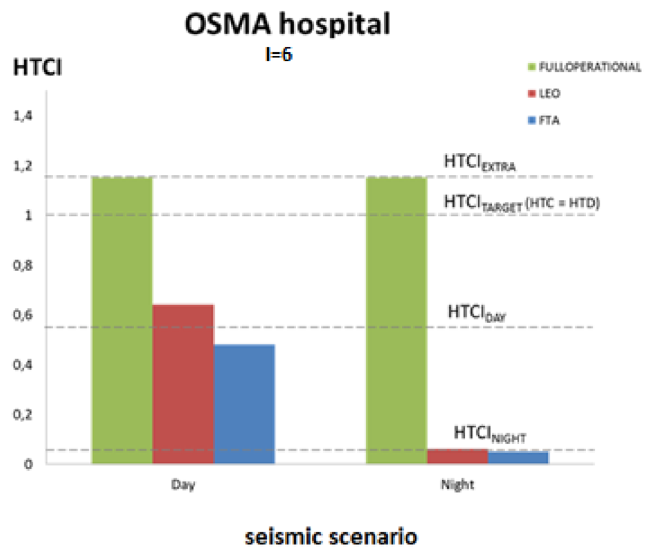

Figure 5.19.: HTCI evaluation at the OSMA hospital for seismic intensity I=6.

The green bar reports the full operational HTCI value with the hospital 100% functional (pre-event) which is HTCI=1.15. This means that with a full operational non-degraded hospital, the medical demand in aftermath of a seismic event (I=6) could be easily complied. 58% and 45% degradations of the pre-event value of the hospital treatment capacity index (HTCI) are assessed by applying the FTA and Leontief models respectively at the day time scenario while for the night scenario a 95% degradation is common for both models.

Moreover equations 18 and 19 would allow to estimate the minimum degradation allowed, in case of I=6 seismic event, to offer an appropriate medical response to the local health demand.

$$HTC_{FULL-OPERATIONAL} - HTD_{HOSPITAL} = HTC_{EXTRA} \quad (18)$$

Once obtained the extra HTC, which represents the maximum loss of performance allowed during the seismic event, it is possible to obtain the corresponding HTC degradation by applying the linear proportion reported in equation 19.

$$HTC_{FULL-OPERATIONAL} : 100\% = HTC_{EXTRA} : X \quad (19)$$

For the Florence hospital case study the value obtained is X=13%. By comparing the allowed degradation with the estimated one, Florence hospital should carry out mitigation strategies able to solve degradation problems for a range between 30% – 45%.

In conclusion, even if there are no significant differences between the two models at the night scenario, the FTA model shows a more “pessimistic” behavior than Leontief for the Hospital treatment capacity at the day scenario.

The Intrinsic Security at the Florence Hospital in case of I=6 seismic event has been already reported in figure 5.11b and showed how FTA model shows a higher IS value (0.7) than Leontief model (0.65) which correspond to a IS degradation of 30% and 34% respectively. This means a more optimistic behavior for Leontief model than FTA for both scenarios night and day.

Last step of the hospital response evaluation to the seismic event with intensity I=6 regards the estimation of the Hospital Performance Index (HPI). According to the equation 17 in chapter 3 and to the case of “city hospital” for the definition of the coefficients η and θ (η=3, θ=2), the calculated HPI is reported in figure 5.20.

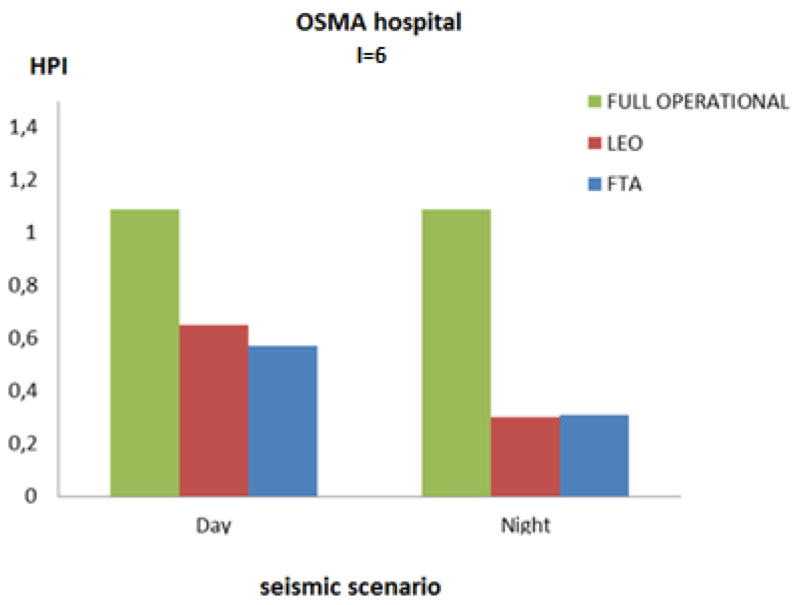

Figure 5.20.: HPI evaluation at the OSMA hospital for seismic intensity I=6.

The HPI=1.09 typical for the fully functional hospital is reduced during an I=6 earthquake, according to the FTA model, by 48% and 71% for the day and night scenarios respectively while Leontief assesses a degradation of 41% and 72% for day and night scenarios respectively.

In conclusion, HPI for both FTA and Leontief models show similar behavior especially comparing the different values for night and day scenarios. A lower HPI during the day scenario is assessed by FTA and a lower HPI for the night scenario is estimated by Leontief.

6. Methodology Validation

6.1. Overview

In order to validate the methodology, both models are applied to the main hospital in L'Aquila in order to compare the outputs with the real ones observed during the L'Aquila earthquake in 2009. The model validation aims to modify and update the inoperability levels [37] in Leontief model (failure vector) and in FTA (basic events) besides the constants η and θ defined in equation 17 in chapter 3. General suggestions on both FTA and Leontief are expected as well.

6.2. San Salvatore Hospital and L'Aquila Earthquake (2009)

The method described in the previous chapters has been validated through its application to the real scenario of L'Aquila earthquake, 2009. On 6 April 2009 a seismic event of intensity 6.3 struck the province of L'Aquila. It caused damage to 100.000 buildings in 57 municipalities, left 67,500 local residents homeless, killed 308 people and injured 1.500, 202 of them seriously [99].

Figure 6.1 shows the San Salvatore Hospital, which is composed by 12 buildings. It is the only hospital in L'Aquila and provides 464 hospital beds and 10 operating rooms.

Figure 6.1.: San Salvatore Hospital in L'Aquila.

By the interviews carried out with the San Salvatore hospital medical direction, it has been possible to assess the functional levels at pre- and post- the seismic event according to the specific medical areas: hospital beds, ICU and OT. The results are reported in table 6.1.

SAN SALVATORE HOSPITAL PERFORMANCE		
pre event operability		
Functional H-beds	Functional Operating Rooms	Functional ICU-beds
464	10	8
post event operability (within 6 hours by the seismic shake)		
Functional H-beds	Functional Operating Rooms	Functional ICU-beds
454	2	8

Table 6.1.: San Salvatore hospital real performance in the aftermath of the 2009 earthquake.

According to the interviews, the medical equipment and the DATA system were the most damaged systems. Moreover, the structural damages caused the loss of the medical gas system (valve rupture) and the TAC rupture (linear accelerator decalibration) due to the strong vibrations during the earthquake.

These damages caused a functionality loss of 80% for the surgical activity and 2% for the hospital beds. No functional losses were estimated for the ICU area.

6.3. Seismic Vulnerability Assessment

Rapid Vulnerability Evaluation

Table 6.2 and table 6.3 show the results obtained by the application of the rapid vulnerability assessment forms described in chapter 2 and personally filled at the hospital area.

		VULNERABILITY			
San Salvatore hospitlal		Structural	Non Structural		
N.	Name		architect	Equipment&Furnishing	basic installations
Delta 1		L	M	M	M
Delta 2		L	M	M	M
PS		L	M	M	M
ALTRI		L	M	M	M

Table 6.2.: Rapid assessment of structural and non-structural vulnerabilities at the San Salvatore Hospital.

As reported in table 6.2, any specific differences according to the structural and non-structural vulnerabilities are assessed amongst the different buildings while for the functional aspects one building includes all the surgical activity of the hospital as well as for ICU beds. Hospital beds are mainly distributed in two buildings which contain almost the 60% of the whole hospital capacity (300/464 hospital beds), see table 6.3.

		VULNERABILITY		BEDS	
San Salvatore hospitlal		Administartaive/organizational		OT	Hospital and ICU
N.	Name	Capability*	Services distribution**		
Delta 1		L	L		150
Delta 2		L	L		150
PS		L	L	10	8 (ICU)
ALTRI		L	L		164

Table 6.3.: Rapid assessment of administrative/organizational vulnerability and beds capacity at the San Salvatore.

Leontief model

The input failures' vector obtained by the evaluation forms according to a seismic intensity (I=6) is reported in the table below.

hospital area	Inoperability level
A - Emergency department	0.03
B – Diagnostic	0.03
C - Surgical operation	0.03
D – ICU	0.03
E - Inpatient ward (hospital beds area)	0.03
F – Morgue	0.03
G - Lab	0.1
H - Crisis room	0.03
I - Internal connection (Lifts, viability, etc..)	0.03
L- Power network	0.1
M - Gas Network	0.1
N - Hydric Network	0.1
O – Back-up generator	0.1
P - Fire System	0.03
Q – Equipment	0.1

Table 6.4.: Input failures' vector evaluated for the L'Aquila hospital (seismic intensity I=6).

The inoperability outputs of the specific medical areas obtained as the combination between the Leontief matrix and the input vector are showed in figure 6.2.

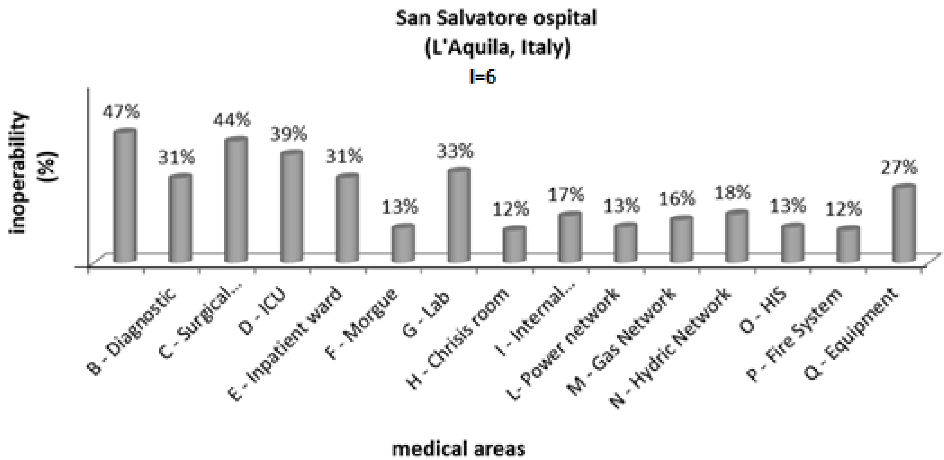

Figure 6.2.: Inoperability outputs per medical area at the San Salvatore hospital.

FTA model

The FTA model application has started with the tree designing process in accordance to each medical area: hospital beds, ICU and OT. Figure 6.3 reports the hospital beds tree while the ICU and the operating theatres can use the same trees developed within the OSMA case study since the one-building configuration is still valid for the San Salvatore hospital as well.

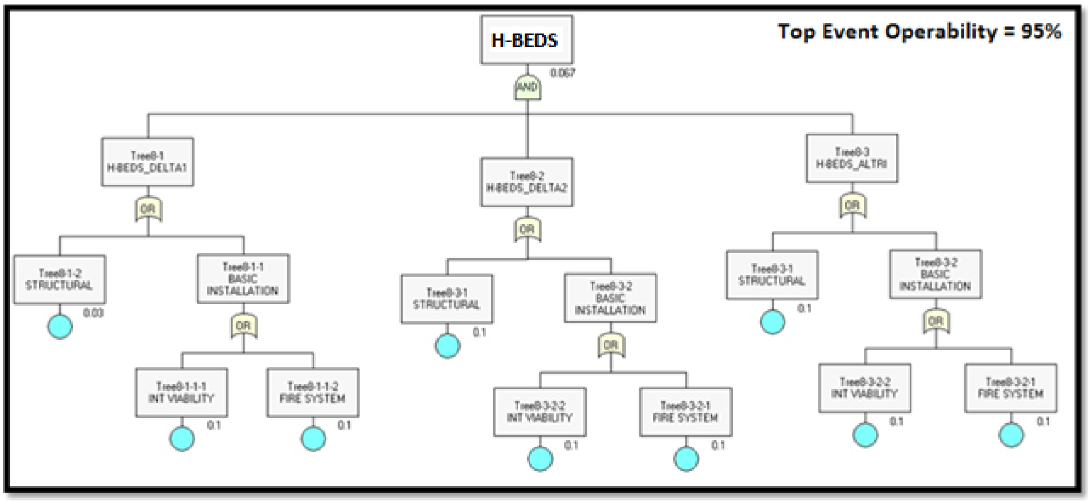

Figure 6.3.: FTA applied to the hospital beds area at the San Salvatore hospital.

It is important to remind how, in the San Salvatore and OSMA hospitals applications, the same configuration of a fault tree does not absolutely mean the same top event operability since the operability value depends also on the basic events operability.

6.4. Performance Validation

With regards to the Leontief model, the evaluation estimated an index HTC=2.8 for the daytime and HTC=0.28 for the night time/holiday scenario. The IS index assumed the value IS= 0.689 and IS= 0.690 for the day and night time/holidays scenario respectively. The HTCs obtained by the FTA application are HTC=2.09 for the day scenario and HTC= 0.21 for the night and holidays.

While the real data (table 6.1) and the equation 11 in chapter 2 define a real post-earthquake HTC=1 with a degradation from the initial value (HTC=5.0 - fully operational) of 80%. Equation 12 estimates as real San Salvatore Intrinsic Security IS=0.979 which consist of a 0.03% degradation from the beginning value.

As reported in figure 6.4, the difference between the HTC estimated by the models and the real case is really high but the FTA model is closer to the real situation than the Leontief one. The deviation between the models and the real case is 109% for the FTA and 180% for Leontief. This means that FTA model is 39% more accurate than the Leontief. With the term real case (REAL) is intended the post event situation of the L'Aquila earthquake on April 6, 2009.

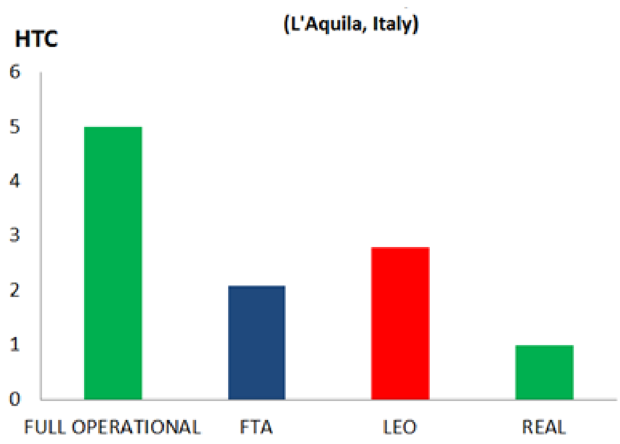

Figure 6.4.: HTC according to the "real case" and to the FTA and Leontief models at the L'Aquila hospital.

Although the L'Aquila earthquake struck at 3.32 am local time, for both the IS and the HTC indices the validation process only considered for the real case comparison the day scenario. This is due to the fact that even if the medical personnel available couldn't get the medical facility, many medical professionals spontaneously came to the hospital reaching the ordinary number of medical professionals in service. Moreover, no significant differences exist between the estimated IS day and IS night for both models.

Figure 6.5 shows the estimated IS compared to the real case one.

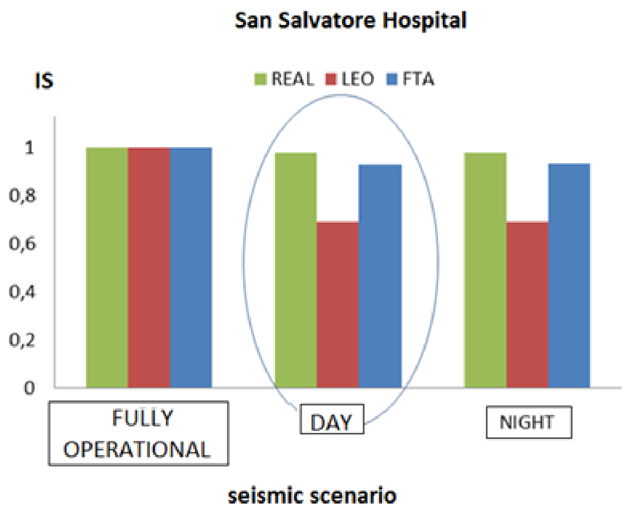

Figure 6.5.: IS according to the "real case" and to the FTA and Leontief models at the L'Aquila hospital.

The FTA model is closer to the real situation than Leontief by showing a relative dispersion to the real case of only 4%. For the Leontief model the deviation is 30% (86% less accurate than the FTA analysis).

6.5. Response Validation

With regards to the medical demand during the L'Aquila earthquake, the number of casualties caused by the event according to the triage code is reported in table 6.5.

L'Aquila earthquake casualties evaluation		
I=6	RED TRIAGED	202
	YELLOW TRIAGED	
	GREEN TRIAGED	1258
	BLACK TRIAGED	308
Source: European Project MICRODIS [99]		

Table 6.5.: Casualties distribution at the L'Aquila earthquake on April 6 2009.

By applying equation 14 the calculated HTD is equal to 6.7, while applying equation 15 and setting the San Salvatore facility as the only hospital in L'Aquila, the resulting $HTD_{HOSPITAL}$(6.7) coincides with the HTD. The subsequent real case HTCI is equal to 0.15.

The HTCI obtained by Leontief application is 0.41 according to the day scenario and 0.04 according to the night/holidays scenario. Moreover, the HPI is equal to 0.17 for daytime exposure and 0.3 for the night/holiday scenario. The HTCI resulting from the FTA application is 0.31 and 0.03 for the day and night/holiday scenarios respectively and the HPI are equal to 0.12 and 0.39 for the different scenarios, day and night/holiday respectively.

Figure 6.6 shows the HTCI comparisons amongst the real situation HTCI (green bar) with respect to the FTA and Leontief (LEO) estimations.

As described previously for the hospital performance validation, although the real case study includes both night and day scenarios, only comparison with the day scenario is carried out because, according to the personnel interviews, any appreciable deviation from available staff and hospital personnel were noticed in aftermath of the earthquake. All the available physicians and nurses living closely to the hospital spontaneously decided to reach it for the emergency cares.

The expected lower presence of staff within the structure depends on organizational and decision which make the most of medical personnel only available on call. Even if it is a rational choice, the availability on call is a really vulnerable element in case of earthquake, since it depends on road viability conditions.

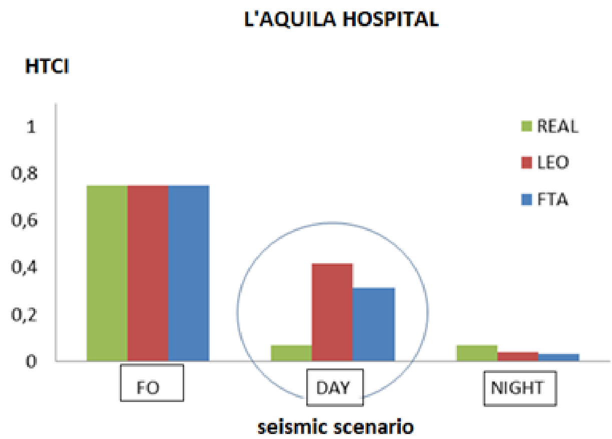

Figure 6.6.: HTCI validation according to the "real case" and to the FTA and Leontief models at the L'Aquila hospital.

Hence comparing the Full Operational mode (FO), which defines the same pre event HTCI for both models and the reality for the day scenario, FTA model provides a more reliable and accurate outcome than Leontief. Precisely, FTA is 30% more accurate than Leontief by showing a HTCI dispersion of 342% for the FTA model and 495% for Leontief.

The last step of the validation process includes the HPI estimation with respect to the real HPI. As figure 6.7 reports, the results are contradictory with respect to the specific indices 'validation as reported in figure 6.5 and 6.6 for IS and HTCI respectively.

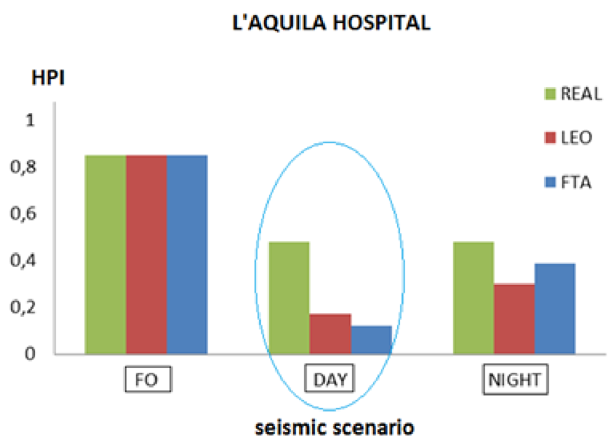

Figure 6.7.: HPI validation according to the "real case" and to the FTA and Leontief models at the L'Aquila hospital.

In fact, although the HPI is a linear combination of HTCI and IS, the HPI comparison shows how the Leontief model is closer to the real situation than the one estimated with FTA, with a relative deviation from the real case of 22%, which is lower than the dispersion obtained with the FTA (28%).

In conclusion the validation showed high models' dispersion compared to the real case. Changes are necessary to the failure input vector coefficients used for the Leontief matrix and for the reliability coefficients in FTA (0.3 for High vulnerability, 0.1 for medium level and 0.03 for low one). Moreover given the contradiction behavior of the HPI index, η and θ coefficients must be included in the modification process as well.

6.6. Validation Outcomes

A sensitivity analysis has been carried out for choosing the right coefficients and minimizing the differences between the real case and the models. The new values are as follows 0.3 for High vulnerability, 0.18 for Medium level and 0.005 for the Low one. As reported in figure 6.8a, the HTCI post-validation dispersion passed to 0% and 40% for FTA and Leontief models respectively.

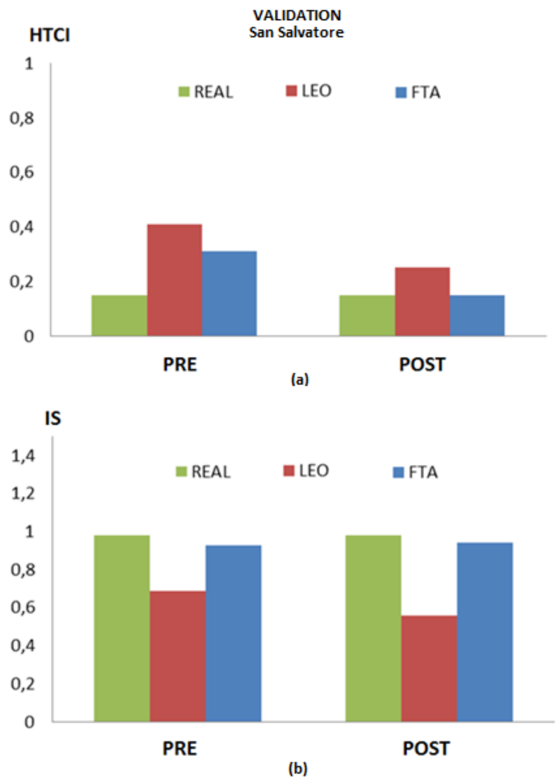

Figure 6.8.: L'Aquila hospital HTCI PRE and POST validation.

With regards to the index IS, the deviation with new coefficients was reduced to 3.6%

and 43% respectively for FTA and Leontief, see figure 6.8b. In general, with the post validation new coefficients the mean deviation from the real case was reduced to 1.8% (173% pre-validation) for the FTA model with a general improvement in accuracy of almost 100% while with regards to the Leontief model, the post validation deviation is 42% (262% pre validation) with a general improvement of 83%.

Finally, according the HPI index, η and θ coefficients have been modified according to the following consideration. Since HTCI is an index with an approximate range of 0-10 while IS only can get values between 0-1, the same difference must be kept for the coefficients as well. Hence, in order to maintain the same proportion, the η parameter should be on order bigger than θ.

The updated values are as follows:

- City Hospital η = 20, θ= 1;
- Country Hospital η = 10, θ= 3;
- Small City Hospitalη = 20, θ= 3.

Figure 6.9 reports the situation pre- and post- validation according to the HPI evaluated with the new coefficients. The FTA model is now closer to the real situation than Leontief confirming the expected situation due to the HTCI and IS specific analysis. The real case HPI is 0.13 with a FTA value of 0.12 and the Leontief HPI=0.17.

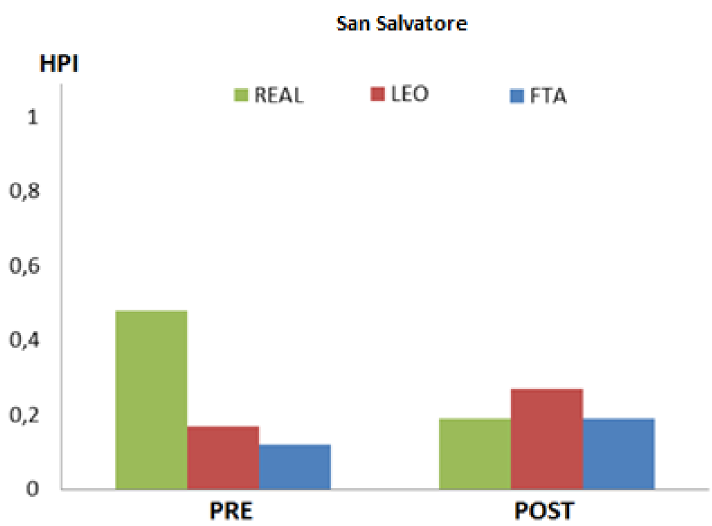

Figure 6.9.: L'Aquila hospital HPI PRE and POST validation.

In conclusion, the new indices for the hospital response assessment have been updated with the post validation coefficients and used for a new application to the OSMA hospital.

Regarding the HTC analysis, only the daytime scenario is considered since the night scenario trend is constantly ten times lower than the day one. With regards to the

Intrinsic Security, only the day scenario is reported in the graphs below since the night time trend is similar to the day one.

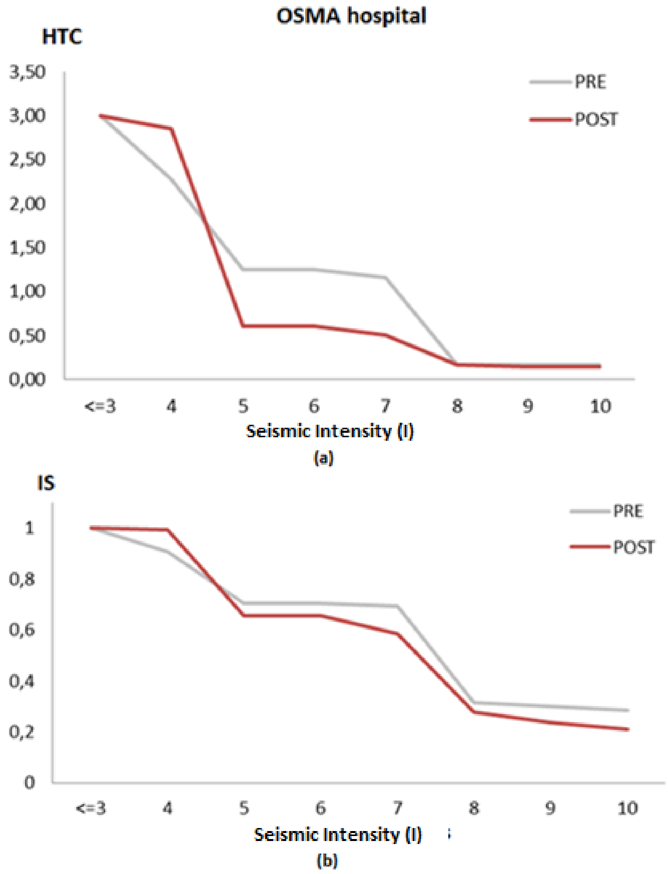

Figure 6.10.: OSMA hospital PRE and POST validation: (a)HTC and (b)IS.

Figure 6.10a shows the new HTC. With respect to the pre-validation, the post-validation trend shows more stability at low seismic intensities (I<4) but the strong degradation of the hospital treatment capacity (HTC) is anticipated at the value I=5. For I>8 both pre- and post-validation indices are similar. Lower levels of HTC are estimated with the post validation coefficients at the medium-high intensities (I=5-7) while a "more optimistic trend" is evaluated for the lowest intensities (I<4). Moreover, the decrease assessed for I=7 depends on the structural contribution to the seismic damages estimation (medium vulnerability) while the step down at intensity I=8 represents the negative contribution of viability and basic installation elements to the hospital vulnerability assessment.

Figure 6.10b shows the IS sensitivity analysis for OSMA hospital in Florence by comparing the pre- and post-validation trends. Although the differences between the pre- and post-validation trends are smaller than the one regarding the HTC, the IS post-validation trend is higher for the lowest seismic levels (I<5) while is lower for the medium and highest ones (I>5). As well as for the HTC trend, IS shows a small decrease at intensity I=7 which depends on the involvement of the structural elements in vulnerability assessment while the decrease at intensity I=8 is given by the contribution of the viability and basic installations' elements to the vulnerability estimation.

7. Risk Assessment - US Case Study(SCVMC)

7.1. Overview

As the aim of this dissertation is to apply a broad-based model to a modern general hospital, and in order to cover the widest range of health structures, the validated methodology has been applied to a US hospital in California. The Santa Clara Valley Medical Center (SCVMC) is one of the four main hospitals situated in San Jose, California – US. The SCVMC is a 600 hospital beds public facility with 12 surgery tables and equipped for air rescue. As reported in figure 7.1, the medical areas are distributed into three main buildings: building “A” which is a modern construction containing administration and pharmacy, building “B” containing 12 surgery rooms, in-patients and 40 ICU beds, and finally building “C” which is the oldest one and contains the emergency department, the helicopter airstrip and a part of the in-patients ward (hospital beds area). Other buildings, which are not showed in figure 7.1, contain basic installation components and support areas such as the laundry or the hospital kitchen.

Figure 7.1.: The Santa Clara Valley Medical Center (SCVMC) in San Josè – CA, US [source: Googlemap].

The San Jose area is within the Santa Clara County and is considered highly seismic as well as for the whole California state. San Josè is situated on a type "C" soil, see figure 7.2[100].

Figure 7.2.: The Santa Clara County soil classification[100].

7.2. Seismic Vulnerability Assessment

Rapid Vulnerability Evaluation

The rapid vulnerability assessment results are described below. Table 7.1 reports the number of hospital and ICU beds and operating tables besides the different vulnerability types and levels assessed for each building by taking into account a seismic intensity I=6. The rapid assessment procedure has been carried out with the support of the facility manager and the chief of construction services at the SCVMC.

I=6		VULNERABILITY						BEDS	
		Structural	Non Structural			Administrative/organizational		OT	BED+ICU
N.	Name		architect	Equipment&Furnishing	basic installations	Capability*	Services distribution*		
1	a	L	M	L	M	L	L	0	0
2	b	L	M	L	M	L	L	12	277+40
3	c	L	M	L	M	L	L		306

Table 7.1.: Vulnerability levels assessed with the rapid assessment procedure at the SCVMC.

All buildings show a low structural vulnerability, especially building 'B' and 'C' which belong to steel moment resistant constructions. Fire risk is really low because no flammable gas is present within the hospital and the level of detection, protection and evacuation measures is high everywhere in the facility. Architectural and basic installation components show a medium vulnerability level because of the presence of covering glasses and external conditioners, especially for building 'C', see figure 7.3a and 7.3b respectively. For the installations, a weak point is represented by the lack of appropriate, robust and healthy (non-rusty) anchorage systems, see figure 7.3c for the medical gas tank. Finally, medical equipment is generally fixed to the floor and all the essential medical areas in case of seismic event are present within the SCVMC (figure 7.3d).

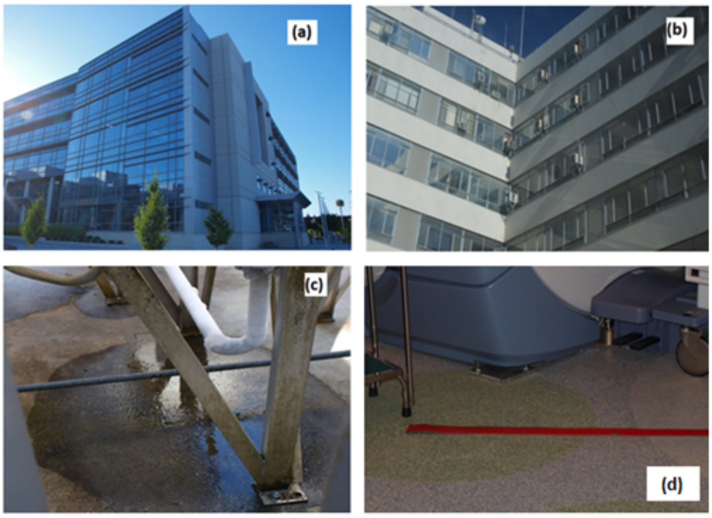

Figure 7.3.: Non-structural vulnerability assessment: (a)Architectural elements and basic installations, (b)inappropriate anchorage, (d)appropriate anchorage.

Moreover, the field assessment showed that some systems' connections are not flexible such as the pipes containing oil supply to back-up generator, see figure 7.4.

Figure 7.4.: Non-structural vulnerability: rigid pipes for back-up generator oil supply.

Pipes rigidity can cause ruptures which can be subsequently responsible for back-up generator malfunctioning and high risk of fire.

Leontief model

The Leontief model has been applied in order to carry out comparisons between the Italian and US case studies for what concerns hospital organization, system degradation at the intensity I=6 and experts interview. Regarding the hospital performance and response evaluation, only FTA model is taken into consideration since it represents the most accurate and reliable model as showed in the previous sensitivity analysis (chapter 6). Two experts were interviewed for the definition of the matrix coefficients and included:

- 1 technical director of facilities;
- 1 emergency department chairman.

The questionnaire consisted of 196 semi-structured questions and considered both expertise and confidence levels. Crisis room was not inserted in the interviews as it is not present in the SCVMC. The highest dependency index 'δ' belongs to the surgical area with a value of 1.99 while the highest gain index 'ρ' belongs to the power system with a value of 2.84. In figure 7.5 is reported the output inoperability levels of each hospital area.

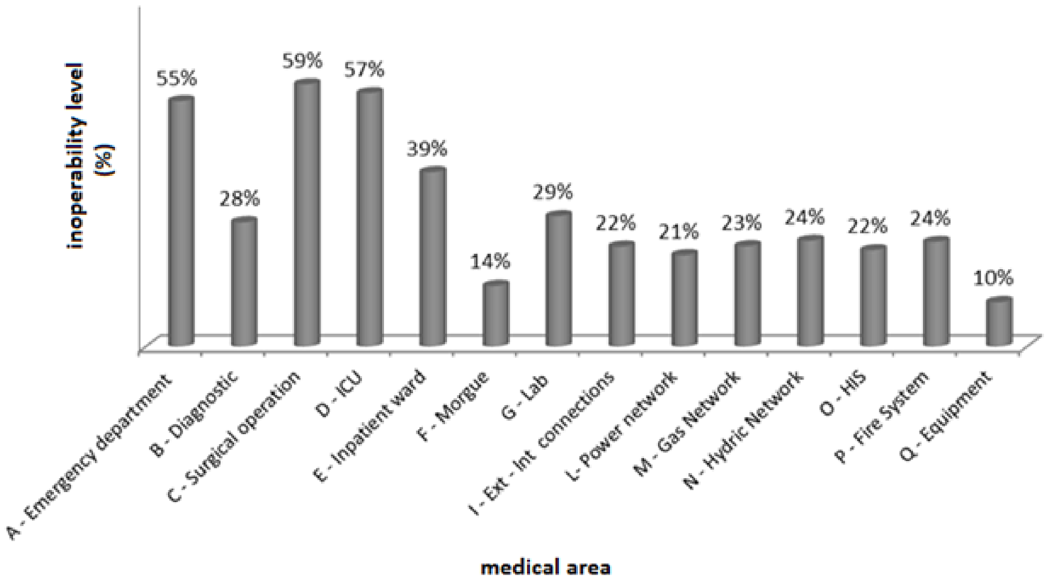

Figure 7.5.: SCVMC output inoperability levels for intensity I=6.

Big differences were estimated amongst the hospital areas: emergency dept., operating theatre, ICU and in-patient wards are the most affected areas while the medical equipment and morgue are the least affected areas.

FTA model

The new FTA model built for SCVMC is reported in figures 7.6, 7.7 and 7.8. The estimated operability is 24.6% for surgical activity, 61.7% for ICU and 87% for the ordinary hospital beds.

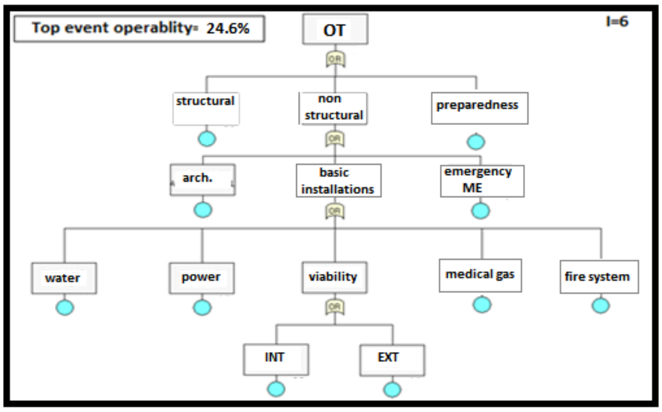

Figure 7.6.: Operating theatre fault tree design at the SCVMC.

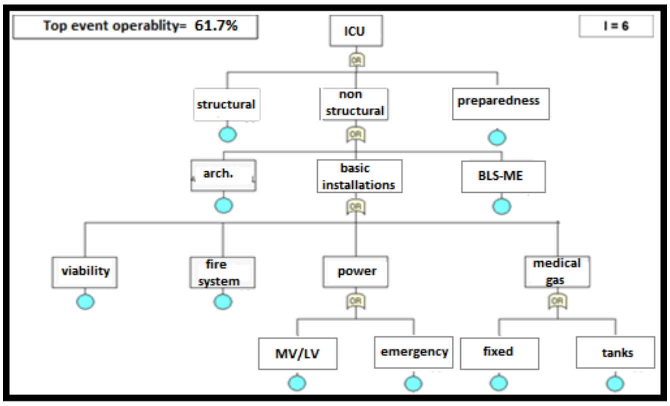

Figure 7.7.: ICU fault tree design at the SCVMC.

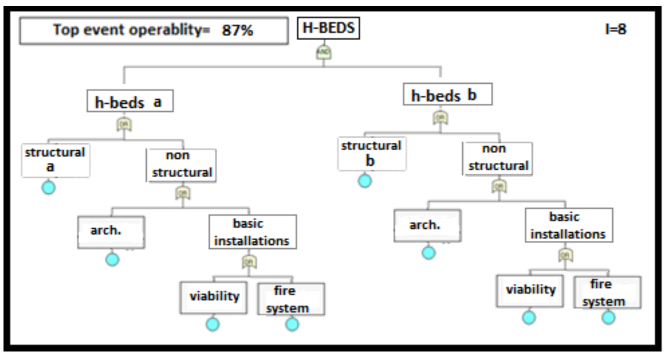

Figure 7.8.: Hospital beds area fault tree design at the SCVMC.

7.3. Performance Assessment

The performance evaluation has been carried out by estimating both indices HTC and IS for the range intensities I=4-10 and it is reported in the next paragraph concerning the sensitivity analysis at the SCVMC.

7.4. Seismic Sensitivity Analysis

7.4.1. System Degradation

With the application of the Leontief model according to the seismic intensities, it is possible to define two different groups of medical areas at the SCVMC: the first one including all those areas remaining below 100% inoperability at any seismic intensities I=1-10 and the second one including all those medical areas getting the 100% degradation/inoperability, see figure 7.9.

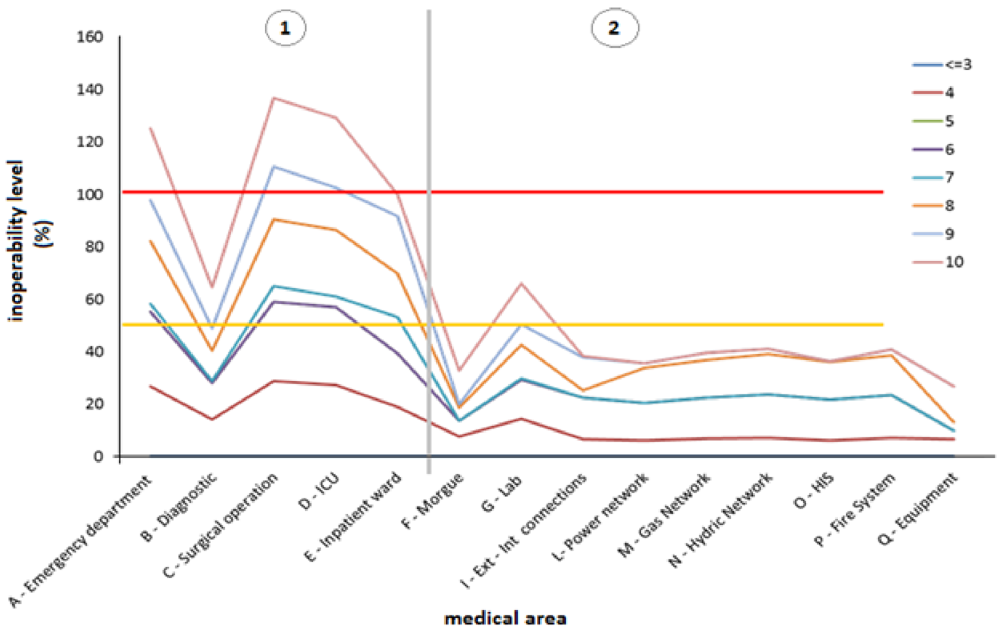

Figure 7.9.: LEONTIEF model results for SCVMC (US) application.

While for low intensities the seismic response follows a more constant trend for all the areas, at the high magnitudes, the differences in seismic behavior are highlighted. Moreover, emergency dept., operating theatre, ICU and impatient ward are the most affected areas while all the basic installations areas and the medical equipment never pass over the 50% inoperability level. Laboratory is over the 50% level only for I=10. Emergency department, surgery, ICU and in-patients areas are the only ones showing a 100% inoperability level. The results of the FTA application are reported in figure 7.10. Three different seismic areas are detectable from the graph according to the seismic intensities: the first area includes I= 1-4, second area involve intensities between 5 and 7 and the third area takes into consideration intensities I=8-10. Seismic magnitude I=5 is an important level for the surgery performance degradation while I=8 represents a crucial point for ICU security. Finally, intensity I=9 represents the critical point for the hospital beds areas.

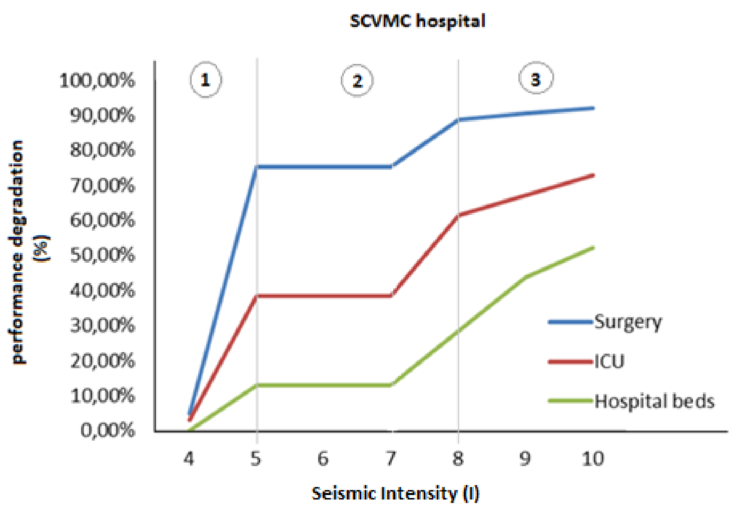

Figure 7.10.: FTA model application to SCVMC (US).

Summarizing the FTA estimation, surgery is the most affected area with over 70% degradation already at the seismic intensities I=5-7 and almost 100% at I=9. For intensity I=8 ICU is over the 50% degradation and the maximum loss is assessed for intensity I=10. Finally, hospital beds area is always below the 50% limit except for the intensity I=10 where the degradation reaches the 50%.

7.4.2. Performance Degradation

Regarding the US case study, figure 7.11 reports the HTC analysis carried out with the FTA model according to the different seismic magnitudes. Blue line shows the HTC during the day time while red line defines the HTC during night/holidays scenario. Big differences exist between the night and day time HTC. For instance, considering a seismic intensity I=4, the night HTC=0.6 presents a value ten times lower than the day one with HTC=5.71. The same situation is valid for each seismic intensity (I=4-10). Night/holidays HTC is almost constant within the seismic range (I=5-10) while for the day scenario the main braking points are for I= 5 (HTC= 1.48) and I=8 where the assessed HTC loses 89% of the pre-event operability with HTC= 0.67. Finally for higher intensities (I>8) the trend is almost constant.

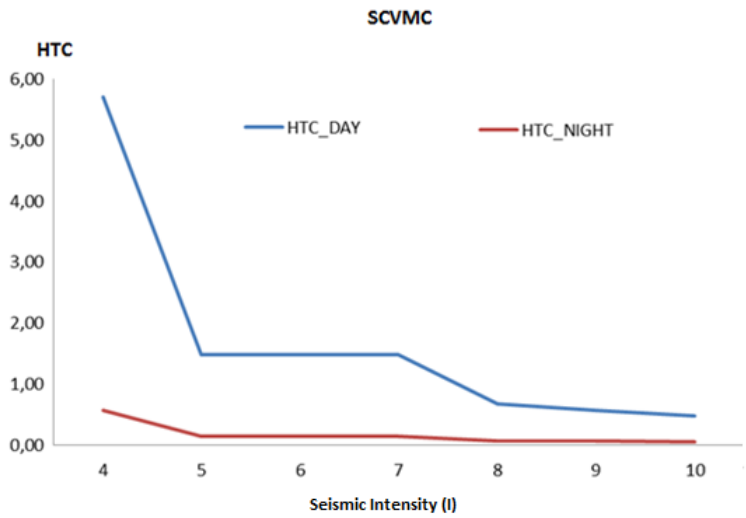

Figure 7.11.: HTC estimation (FTA model) at the SCVMC (US).

Regarding the Intrinsic Security (IS), the analysis reported in figure 7.12 in accordance to the different seismic magnitudes has been carried out with the FTA model application. The blue line shows the IS trend during the day time while the red line defines the IS for night time and holidays scenario. No appreciable differences are estimated between the night/holidays and day time. Both indices have an almost linear trend with two main breaking points: the first one at the intensity I=5 corresponding to a 15% degradation from the pre-event value (IS=1) and the second given by the intensity I=8 which provides with a 30% degradation. Finally the estimated degradation for intensity I=9 corresponds to 40% degradation while for I=10 there is the maximum degradation (IS=0.5).

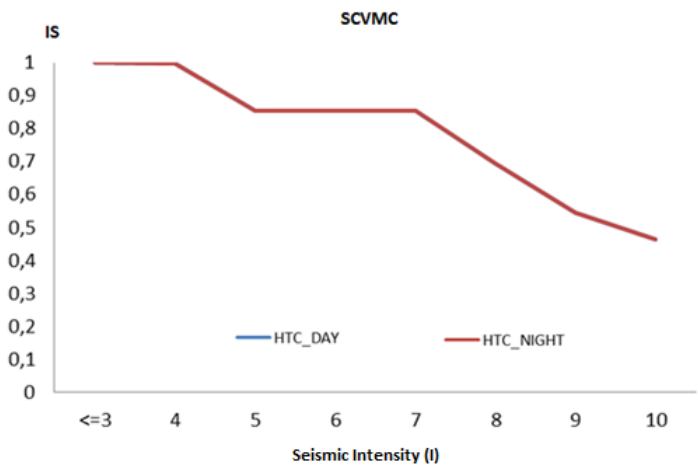

Figure 7.12.: IS estimation (FTA model) at the SCVMC (US).

7.5. Response Assessment

The San Francisco I=8 1906 earthquake has been considered as scenario for the casualty estimation at the Santa Clara County. A death toll of 103 was paid by the county which consisted at that time of 50.000 inhabitants. The same number was chosen for the current assessment because, although the strong increase of population (almost 2.000.000 inhabitants currently) safer constructions have been built on a geological ground safer than San Francisco.

For the estimation of severe casualties the following hypothesis has been made: use the 'Deaths Severe Ratio' coefficient (DSR) used by the SIGE software of the Italian Civil Protection Department [98] in the Florence case study (DSR=1.5). A total of 153 severe casualties have been taken into consideration for the case study.

Hence, by applying equation 14 the HTD assumes the value of 51 patients which represents the total medical demand in Santa Clara County caused by a I=8 seismic event.

Moreover, the use of equation 15 permits to evaluate the working load estimated for each facility in the area. Since the SCVMC is one of the four composing the health system in the Santa Clara County, the SCVMC should face with a $HTD_{HOSPITAL}$ =1.28 patients per hour. Regarding the HTCI evaluation at the seismic intensity I=8, the values for both night/holidays and day scenarios are 0.05 and 0.52 respectively.

As the seismic intensity I=8 does not permit to obtain reliable and stable data from the Leontief model, only FTA model has been applied for the risk assessment and treatment phase at SCVMC. As reported in figure 7.13, a HTCI =0.52 means that only half of the whole assessed medical demand can be satisfied in aftermath of the I=8 earthquake during the day time at the SCVMC. For the night time scenario, the model estimates that only 5% of the medical demand can be satisfied. A HTCI=1 would be the minimum value ($HTCI_{TARGET)}$ for an appropriate scenario where the whole medical demand is completely coped by the hospital.

The green bars show the pre-event HTCI when the hospital is fully working and 100% functional ($HTCI_{PRE\text{-}EVENT}$=4.69). This means that with a full operational hospital, the medical demand in aftermath of a seismic event with intensity I=8 could be easily complied.

Equations 18 and 19 allow to estimate the maximum degradation allowed, in case of a intensity I=8 seismic event at the SCVMC. Once obtained the HTC_{EXTRA}, which represents the maximum allowed loss during the seismic hospital degradation, it is possible to obtain the corresponding HTC degradation by applying the linear proportion in equation 19.

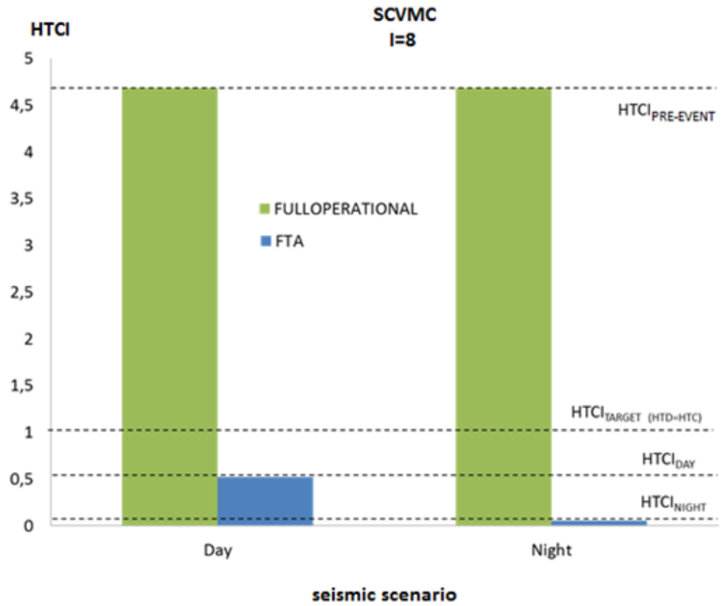

Figure 7.13.: HTCI estimation at the SCVMC for a intensity I=8.

For the US hospital case study the obtained value is 72%. HTC=0.67 is the assessed value for I=8 earthquake at the SCVMC and it represents the 90% degradation from the pre-event value. This means that eventual direct mitigation strategies at the SCVMC should be able to solve degradation problems for HTC about 20%.

The Intrinsic Security at the SCVMC in case of I=8 seismic event is reported in figure 7.14. The FTA model does not show any difference between the night and day scenarios for both models (IS=0.69).

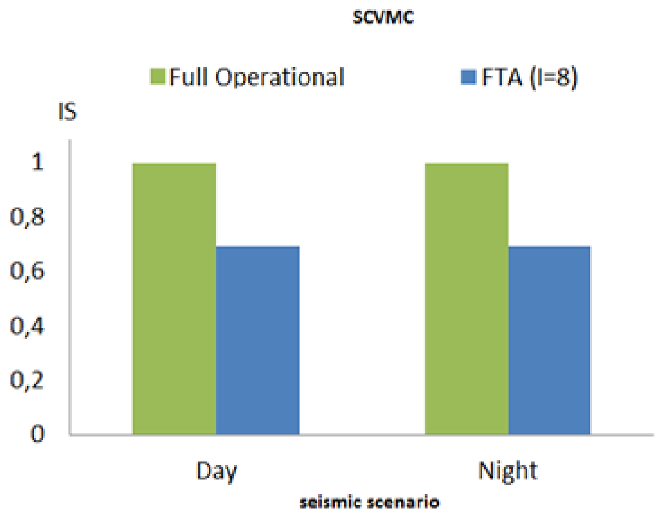

Figure 7.14.: IS estimation at the SCVMC for a intensity I=8.

Last step for risk assessment methodology applied to the SCVMC case study is the estimation of the Hospital Performance Index (HPI). According to the equation 17 and to the case of "city hospital" for the definition of the coefficients η and θ (η=20, θ=1), the SCVMC HPI is reported in figure 7.15. From a HPI=3.21 typical for the fully functional hospital, the degradation assessed by the FTA model is 83.45% (HPI_{DAY}=0.53) and 97.35% (HPI_{NIGHT}=0.09) for the day and night/holidays scenario respectively.

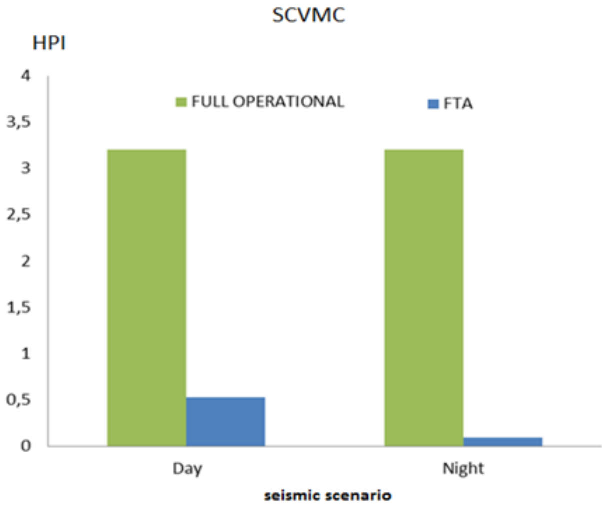

Figure 7.15.: HPI estimation at the SCVMC for a intensity I=8.

7.6. Comparison With the Italian Case Study

7.6.1. Hospital Vulnerability

Rapid Vulnerability Estimation

According to the rapid vulnerability forms, the following comparisons can be suggested between the OSMA hospital (with the post validation coefficients) and SCVMC. By considering a common seismic intensity I=6 for both cases, the SCVMC shows a better seismic behavior for medical equipment and hospital capability with a "low "estimated level of vulnerability against a "medium" level for OSMA hospital. This is mostly due to the lack of the equipment anchorage and the missing of the blood bank area at the Florentine hospital. While for the seismic intensity I=8 both cases have reveled a high vulnerability for basic installations and systems with the SCVMC presenting lower structural, architectural and capability vulnerabilities.

Leontief Model

According to Leontief model outcomes the following comparisons between US and Italy cases can be made:

- By considering I=6 for both studies, the Italian hospital showed that all the medical areas' degradations remain within the 50% inoperability limit while for the US case, all the areas' degradations remain within the 60% threshold;

- By considering I=8 for both hospitals, the Italian case showed that the emergency department, surgery, ICU and inpatients areas reach the 100% degradation limit while for the US case, all the areas' degradations remain within the 85% value;

- By considering the sensitivity analysis carried out by taking into consideration the seismic levels I=4-10, the plumbing system is more damaged in US than in Italy (no water tanks' back up are available in US);

- Medical equipment is the most affected technical area in Italy while in US is the least hit (it is due to the anchorage policy carried out in US);

- The most affected areas are the Emergency department and the Surgery for OSMA hospital and SCVMC respectively;

- Generally, for highest seismic intensities (I=8-10) US hospital shows a better response.

FTA model

With regards to the FTA model application, figure 7.16 shows the comparison concerning the following medical area degradations: surgical area, ICU and inpatients. For all the seismic intensities, surgical activity, ICU and inpatients wards show lower estimated performance degradations at the SCVMC. For the surgical area, similar trends are obtained for both cases even if the US degradation is always 5-10% lower than the Italian one. The same behavior involves the ICU trends. The biggest difference stands for the inpatients ward which shows, for the US application, a much lower degradation than the OSMA one. The difference increases more and more by increasing the seismic intensities. Moreover, for the inpatients ward big differences regarding the fire protection systems installed in SCVMC exists compared to the OSMA hospital.

Finally, for all the medical areas the comparison shows a safer structural behavior at the US SCVMC compared to the OSMA hospital especially by considering high seismic intensities.

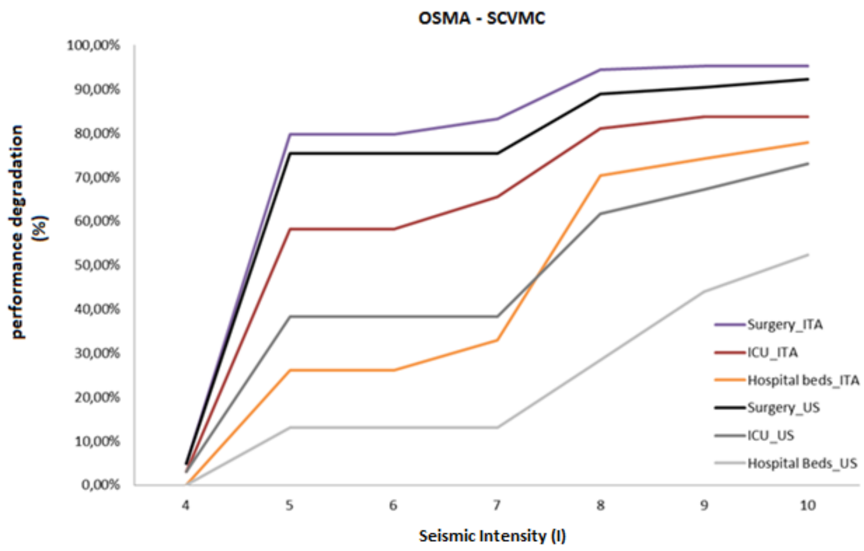

Figure 7.16.: Medical areas' degradation concerning the OSMA hospital and SCVMC case studies.

7.6.2. Hospital Performance

By considering the hospital performance evaluation, following the performance indices 'HTC' and 'IS' referred to OSMA and SCVMC hospitals are compared.

HTC evaluation is shown in figure 7.17.

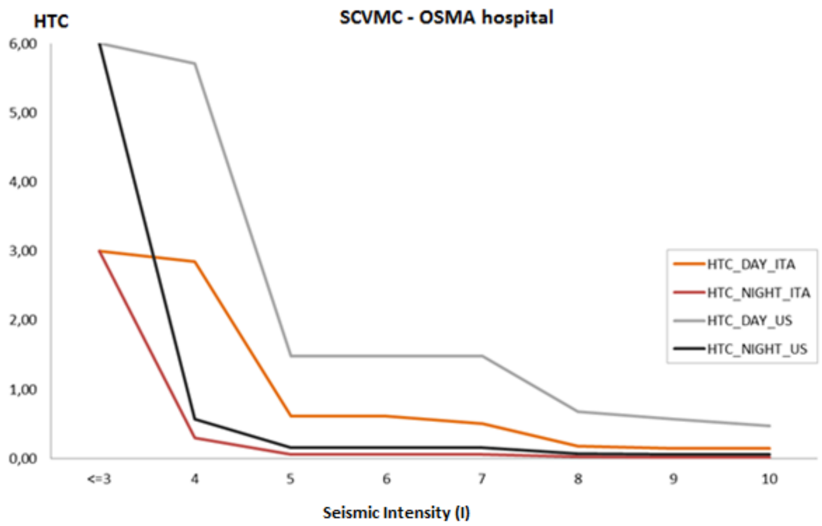

Figure 7.17.: HTC degradation concerning the OSMA hospital and SCVMC case studies.

The starting US pre event HTC (I<=3) is two times higher than the OSMA hospital with HTC_{SCVMC}= 6 and HTC_{OSMA}= 3 but the degradation trends are similar even if the punctual values at each seismic magnitude are higher for the Florence hospital, except for intensities I=4-6 where the HTC indices have similar degradation levels (0-4%).

Moreover, by considering the highest seismic intensities, the difference in degradation increases with a maximum deviation for I=7 which is equal to 8% higher, while for I=8, I=9 and I=10 the differences are 6%, 4% and 3% respectively higher than OSMA hospital.

The IS evaluation is showed in figure 7.18. The Italian hospital degradation is higher for all the seismic magnitudes. The higher is the seismic intensities and the higher is the difference between the IS values referred to the SCVMC and OSMA hospital. Moreover, IS_{SCVMC}shows a constant trend for the middle intensities (I=5-7) while the IS_{OSMA} constantly decreases. The maximum degradation is almost 80% for the OSMA hospital and almost 50% for the SCVMC. This shows a behavior for the IS_{SCVMC} which is 40% better than IS_{OSMA}.

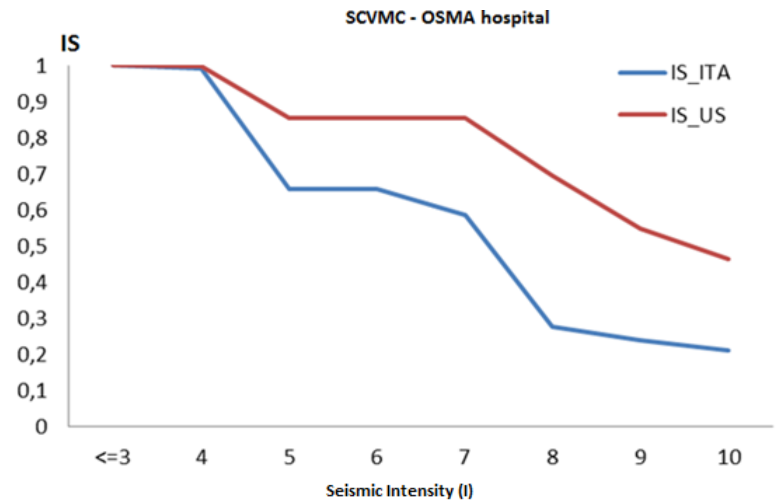

Figure 7.18.: IS degradation concerning the OSMA hospital and SCVMC case studies.

7.6.3. Hospital Response

First of all it is necessary to remind the medical demand scenario regarding both the Italian and US case study. For the Italian scenario, the total hit population considered in the study is around 1.200.000 people with a $HTD_{HOSPITAL}$=2.6 derived by the presence of 5 main hospitals while for the US case study, the affected population is around 1.800.000 people with a $HTD_{HOSPITAL}$=1.3 derived by the availability of 4 main hospitals.

Figure 7.19 shows the HTCI comparison between the two case studies. For both scenarios day and night/holidays, SCVMC shows a higher hospital response than the Italian one which is estimated on the double. Nevertheless, for both scenarios the minimum $\mathrm{HTCI}_{\mathrm{TARGET}}$ is missed and strong decreases are estimated for the night/holidays scenario.

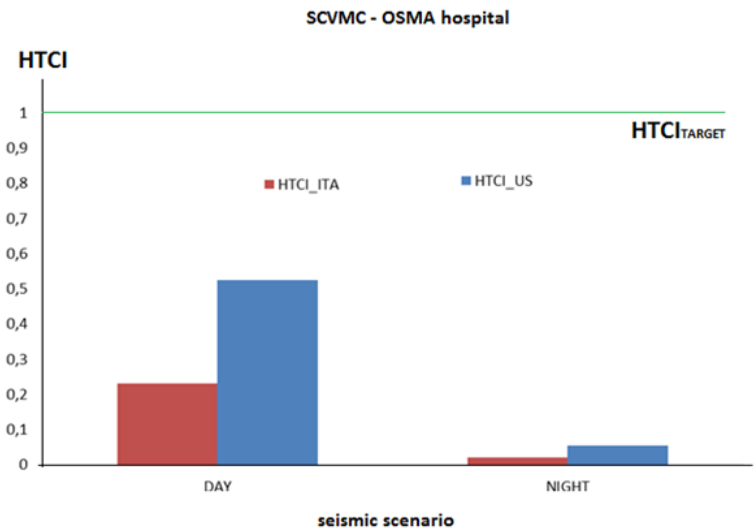

Figure 7.19.: HTCI estimation concerning the OSMA hospital and SCVMC case studies.

With regards to the HPI evaluation, the SCVMC scenario provides a better response than the OSMA hospital even if both are not able to cope with an appropriate health response in case of seismic event, see figure 7.20.

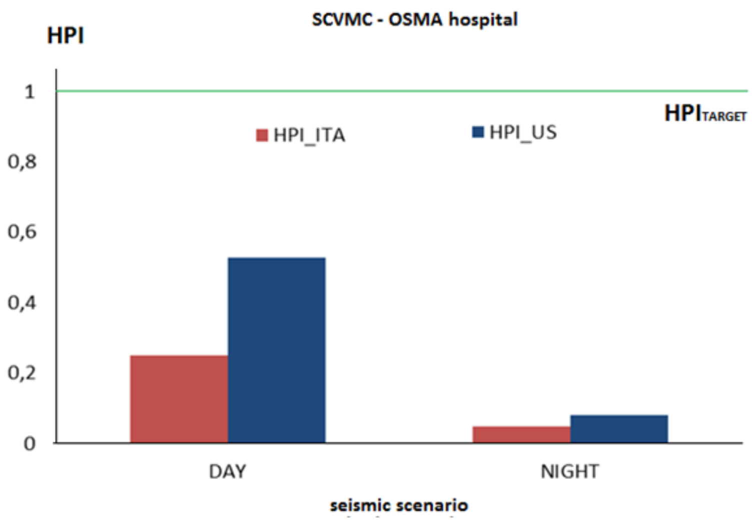

Figure 7.20.: HPI estimation concerning the OSMA hospital and SCVMC case studies.

In the next chapter, both scenarios will be analyzed and treated for an accurate risk mitigation process in order to define the most efficient and appropriate interventions which could be able to provide the minimum level of hospital response (HPI_{TARGET}, $HTCI_{TARGET}$ and IS_{TARGET}).

8. Risk Mitigation at OSMA and SCVMC

8.1. Overview

In this chapter is reported the risk mitigation methodology of a modern hospital through the US (SCVMC) and Italian (OSMA) case studies. Only the FTA model has been used in the analysis as the most reliable and accurate model. The mitigation activities described in the next paragraphs aim reduce the estimated seismic risk by applying different retrofitting measures and analyzing the subsequent security, performance and economic impact on the hospital. This approach is essential for identifying the most efficient strategies for reducing the seismic risk in health structures.

8.2. OSMA Hospital

The risk mitigation regarding the Florence hospital takes into consideration the same seismic scenario used for the risk assessment previously described which has included both the hospital system and the specific hazard impact caused by a seismic intensity I=6. As reported in the hospital vulnerability assessment in Florence (chapter 5), the goal of the risk reduction procedure is reducing the “unfulfilled medical demand” for HTC.

Figure 8.1 shows how only 23% of the medical needs are fully complied with a 77% gap to the $\mathrm{HTC_{TARGET}}$ (2.60 patients per hour).

Regarding the intrinsic security (IS), the aim of reducing the “unsecure area” corresponds to a gap of 30% of the whole inpatients area, see figure 8.2.

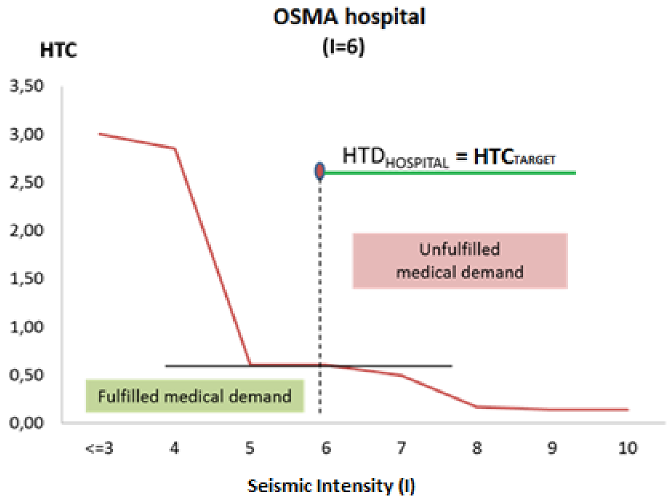

Figure 8.1.: OSMA hospital response assessment (HTC).

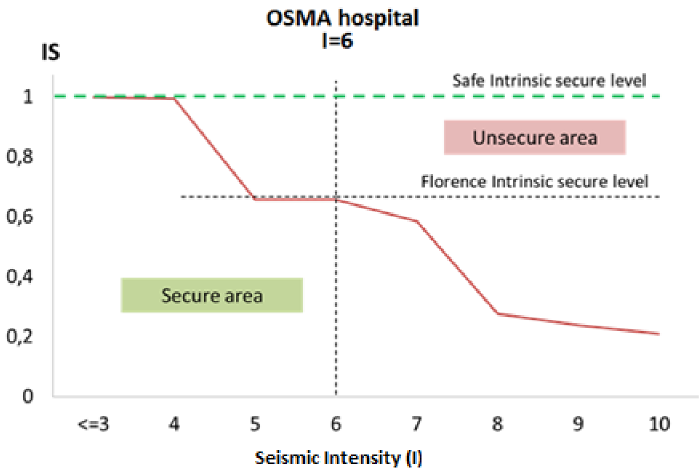

Figure 8.2.: OSMA hospital response assessment (IS).

Following are reported the HTC_{OSMA} simulations according to the different type of interventions described in chapter 4.

8.2.1. Direct Actions

Hospital performance

Figure 8.3a shows the simulation resulting from the application of type 2 actions with respect to the current IS_{OSMA} and which include non-structural interventions to medical devices, office equipment and architectural elements. Appreciable improvements are evaluated for IS at the seismic intensity I=6 where, with respect to the current situation, the simulated one leads to a reduction of 20% of the unsecure area which corresponds to 10% improvement of the current situation. Regarding type 3 actions, the IS_{OSMA} improvement is higher than the previous one by showing a 20% reduction of the current "unsecure areas", see figure 8.3b.

Figure 8.3c shows the mitigation effects of applying type 4 actions. The night time scenario reaches the performance level of the day time while no improvements are appreciated with respect to the current situation for the day scenario.

Finally figure 8.3d shows the mitigation strategies effects on IS_{OSMA} by simulating a structural retrofitting for the hospital. Appreciable effects can be evaluated only at the highest intensities I=7–10, while any differences have been assessed between night and the day scenarios.

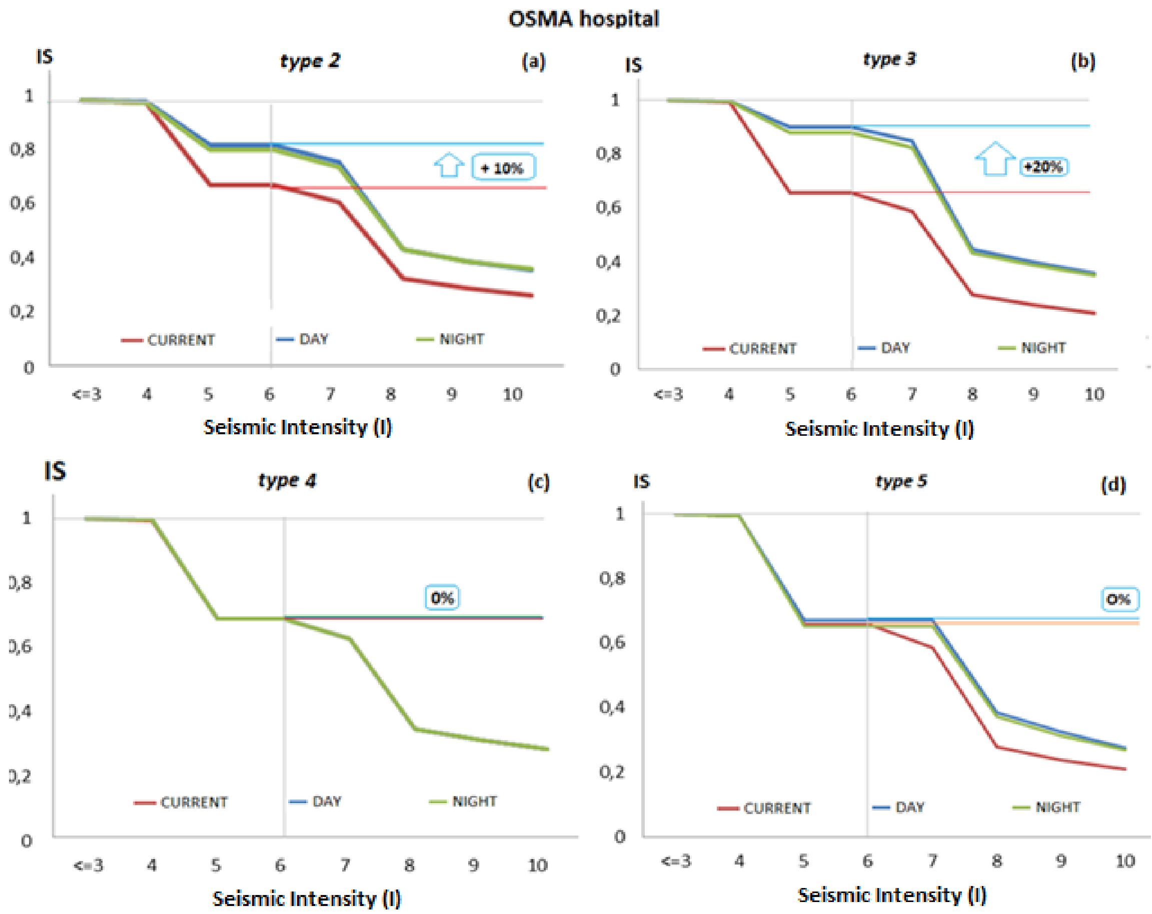

Figure 8.3.: Simulation of direct actions at OSMA hospital according to IS. Type 2(a), type 3(b), type 4(c) and type 5(d).

Figure 8.4 shows the simulation of the mitigation strategies on IS by applying the non-structural retrofitting by involving type 3 and type 2 actions. The type 4 has not been included since it only effects on night/holidays scenario. For intensity I=6 the simulation provides $IS_{OSMA}=IS_{TARGET}$ which guarantees almost a 100% secure areas (IS=0.99). Moreover, the simulated IS_{OSMA} only starts decreasing at the highest intensities (I=8-10) with a maximum degradation at intensity I=10 (IS_{OSMA}= 0.5).

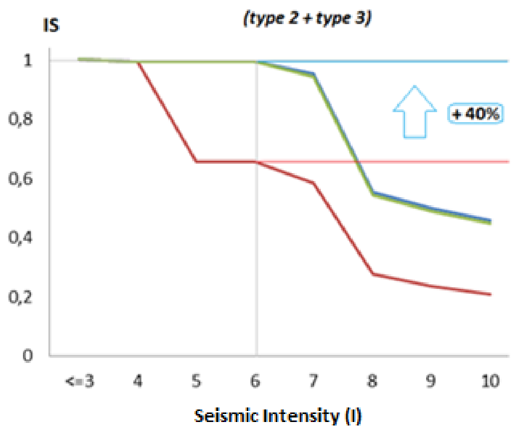

Figure 8.4.: Type 2 and 3 actions for risk reduction at the OSMA hospital (IS_{OSMA}).

A further simulation is represented by adding the contribution of the structural retrofitting to the previous one (type 2 + type 3). Figure 8.5 compares this simulation scenario (NS+S) with the type 2 plus type 3 measures (NS). Only the day scenario is shown because no differences are evaluated in the night/holidays one. At the intensity I=6 no differences are perceptible while for the highest intensities (I=7-10) the (NS+S) simulation shows a higher IS_{OSMA} (+10%) than the (NS) one.

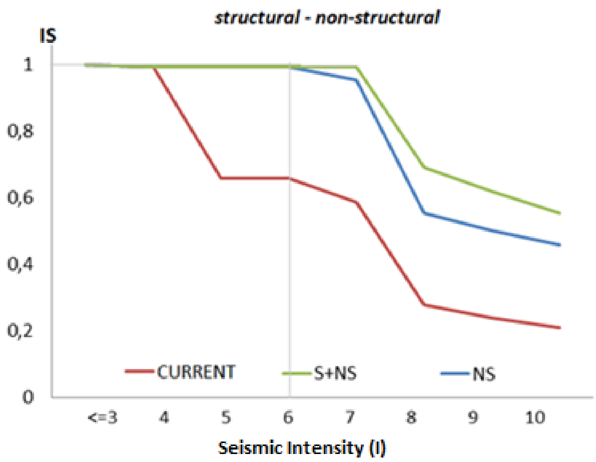

Figure 8.5.: IS_{OSMA} comparisons between (S+NS) and (NS).

The risk mitigation procedure is now applied to the HTC in order to complete the evaluation of the hospital performance. Figure 8.8 shows the simulation effects by applying the direct interventions compared to the current situation for the day time. The simulated scenarios include both day and night/holidays scenarios. Figure 8.6a describes the outcomes resulting by the type 2 retrofitting simulation. Perceptible improvements are assessed for the seismic range I=5-7 (+0.28) regarding the day scenario. The night time scenario trend is following the day time trend but with ten times lower values.

Figure 8.6b shows the simulation effects of type 3 actions. The HTC_{OSMA} improvement is about 218% higher than the current one with a day value of 1.94 for the seismic intensity I=6. High improvements are also given for the seismic range I= 5-7, while for the highest intensities (I=8-10) the HTC_{OSMA} is 164% higher than the current value. The night scenario gives almost constant trend which is never higher than HTC_{OSMA}=0.4.

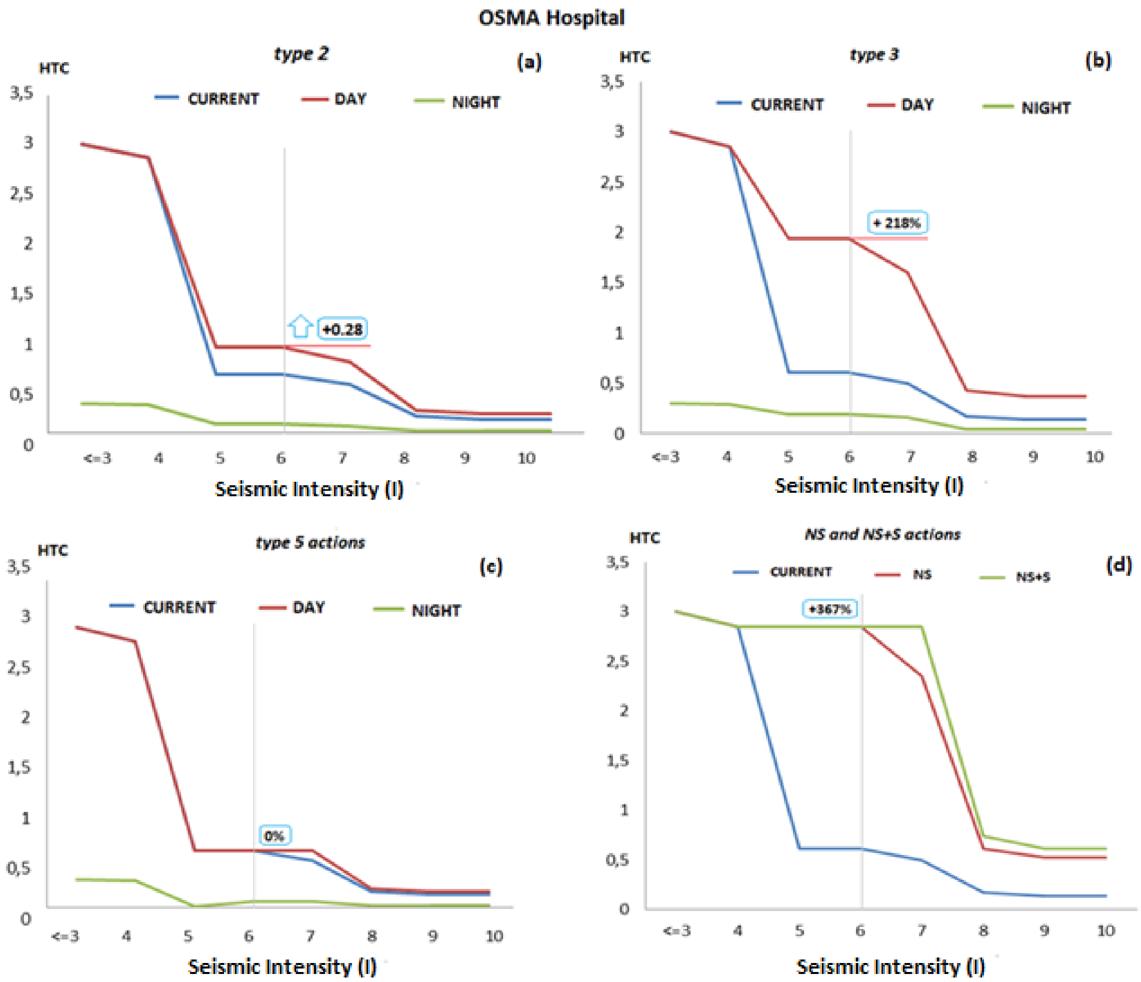

Figure 8.6.: Retrofitting simulations on HTC at the OSMA hospital. (a)type2, (b)type 3, (c) type 5 and (d) comparison between (S+NS) and (NS) measures.

Type 4 measures simulation only provides the same value for both the current and simulated HTC_{OSMA}.

Figure 8.6c reports the effects of type 5 retrofitting for both day and night/holidays scenarios. Appreciable improvements are estimated for the day scenario at seismic intensity I=7 (+22%) while for I=6 no differences are shown.

Finally, figure 8.6d shows the comparisons between the simulation effects of non-structural actions 'NS' (type 2 + type 3) and the non-structural plus structural interventions 'S+NS' (type 2 + type 3 + type 5). Only the day scenario is analyzed. No appreciable differences or improvements are estimated for the seismic intensities I=1-6, in the seismic range (I=5-7) both scenarios almost maintain the initial value (HTC=2.85) which corresponds to a 367% improvement of the HTC current condition. For the highest magnitudes, 'NS+S' actions show higher HTC than NS scenario. For intensity I=7 the simulated HTC_{OSMA} is 2.85 also for the seismic level I=7 (+470% improvement) and for the highest intensities (I=8-10) the general improvement of 'NS+S' and 'NS'is 335% and 270% respectively.

Hospital response

The OSMA hospital response for a seismic intensity I=6 is reported in figure 8.7 which shows the current HTCI post-event degradation. The HTCI is strongly reduced from the initial pre-event value (HTCI=1.15) to the post-event one (HTCI= 0.23).

As already done for the IS_{OSMA}, in the next paragraphs the effects of the retrofitting simulations according to the type of actions on $HTCI_{OSMA}$ for the intensity I=6 are reported.

Figure 8.7a shows the simulation effects of type 2 actions on OSMA hospital and estimates a 48% improvement of the current HTCI for both day and night/holidays scenario. Figure 8.7b shows the effects of type 3 actions. A 226% improvement of the current HTCI has been assessed for both day and night scenario. The effects regarding the type 4 actions focus just on the night scenario which reach the same HTCI value of the current day scenario HTCI, passing from 0.02 to the simulated value of 0.23. Regarding the type 5 retrofitting simulation, no significant improvements have been assessed for the seismic level I=6 for both day and night scenario.

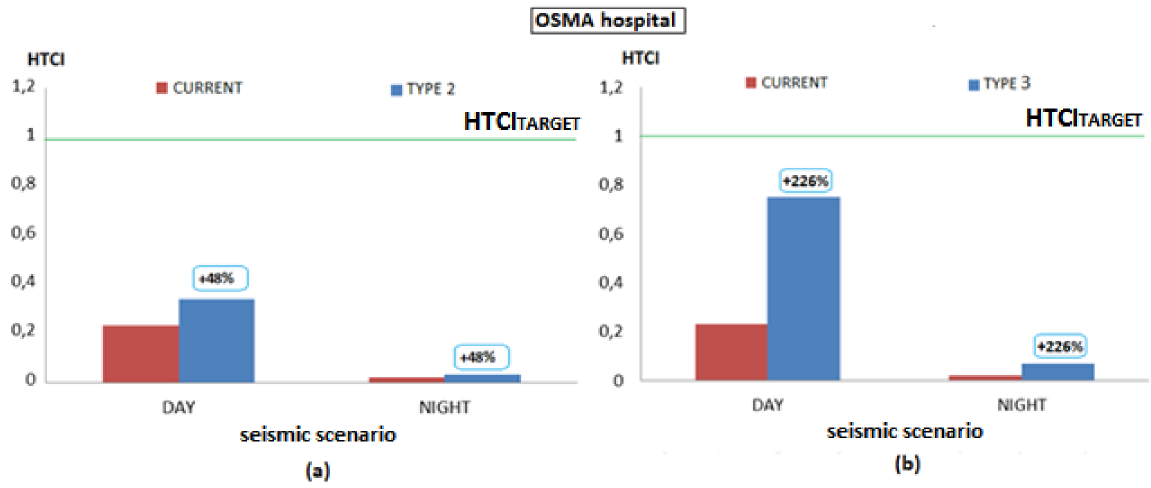

Figure 8.7.: “Type 2 and type 3” actions for risk reduction at the OSMA hospital ($HTCI_{OSMA}$).

Figure 8.8 shows the comparison between the application of non-structural mitigation strategies (NS) and the application of non-structural actions plus structural interventions (NS+S) without taking into consideration the type 4 measures. For the OSMA hospital, structural retrofitting is not necessary to comply with the medical demand caused by a a seismic event with intensity I=6.

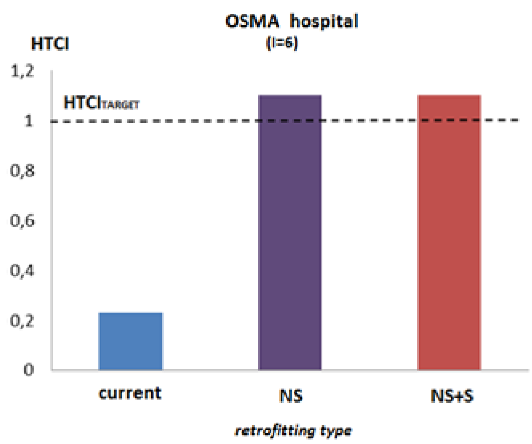

Figure 8.8.: HTCIOSMA comparisons between (S+NS) and (NS) retrofitting.

Figure 8.9 shows the current HPI at the Florence hospital at I=6 seismic intensity for both day and night/holidays scenario. The aim of the retrofitting strategies is reducing the gap between the current estimated HPI (0.75 and 0.95 for day and night scenarios respectively) and the HPI_{TARGET}. Moreover, the maximum acceptable loss (HPI=0.15) is provided by the difference between the pre-event HPI_{OSMA} (1.15) and HPI_{TARGET} 0.15.

Figure 8.9a shows the effects resulting from the simulation of type 2 actions on the current HPI. The simulated HPI_{OSMA} improved with respect to the current one for both day (44%) and night/holidays (40%) scenarios.

While figure 8.9b reports the effects of type 3 actions. The simulated values (HPI=0.75) and (HPI=0.10) correspond to a 204% and a 120% improvement for day and night/holidays scenarios respectively.

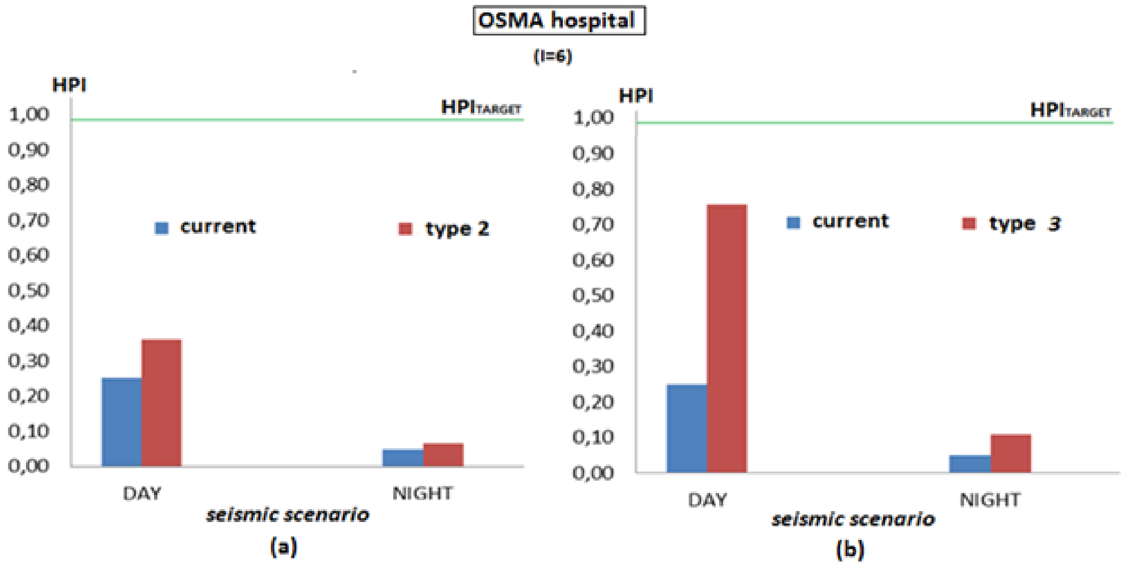

Figure 8.9.: "Type 2 and type 3 actions" for risk reduction at the OSMA hospital (HPI_{OSMA}).

No improvements are obtained for the day scenario according to the type 4 actions while for the night/holidays HPI there is an improvement by 400%.

According to the structural retrofitting defined by type 5 actions, no improvements with respect to the current HPI have been assessed for both day and night scenarios at the intensity I=6.

Figure 8.10 reports the comparison between the simulations of non-structural (NS) mitigation strategies and non-structural plus structural interventions (S+NS). Both cases have been analyzed without taking into consideration the type 4 actions. For the day scenario the HPI_{TARGET} is successfully reached by the application of both strategies. Structural retrofitting is unnecessary for the OSMA seismic risk mitigation at seismic intensity I=6. The total improvement with respect to the current HPI daytime index is around 336% with a final HPI_{OSMA}=1.09.

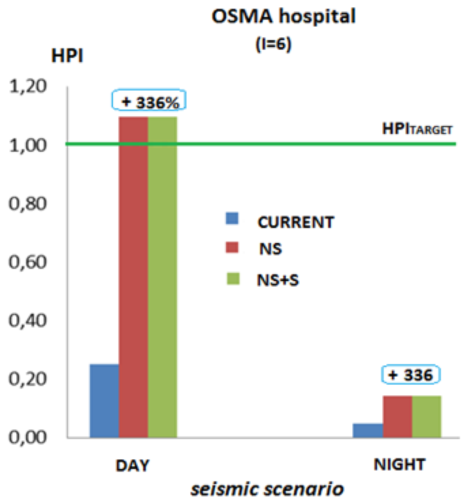

Figure 8.10.: HPI_{OSMA} comparisons between (S+NS) and (NS) retrofitting.

8.2.2. Indirect Actions

Hospital response

The risk reduction at the OSMA hospital by the use of the indirect actions is described as follows. In order to get $HTCI_{TARGET}$ (HTCI=1), the indirect measures must guarantee an improvement of 0.77 for the HTCI which corresponds to a HTC improvement of 2.00 patients/hour. This means a HTC value equal to the $HTD_{HOSPITAL}$=2.60. According to equation 11 in chapter 2, 4 extra surgery tables ($\gamma_1 = 10$) are necessary (option 1) in order to successfully cope with the medical needs. This corresponds to an aerial medical evacuation of 2 patients per hour (option 2), see figure 8.11.

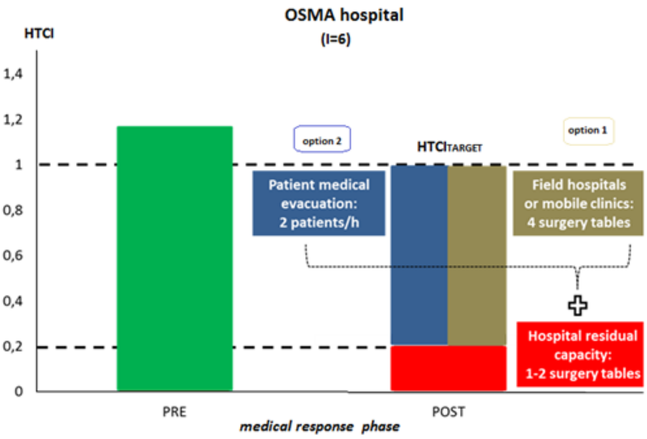

Figure 8.11.: OSMA hospital risk reduction with the application of indirect actions (HTCI).

Regarding the intrinsic security, any indirect intervention can be used for improving this parameter since the indirect actions belong to the coping phase of the medical response and do not take into consideration the pre-event security level of medical occupants.

Finally, the HPI improvement is reported in figure 8.12. Because of the impossibility to operate on the intrinsic security through the indirect interventions, the post mitigation HPI, obtained by the HTCI indicated in figure 8.11, provides a final value 0.97.

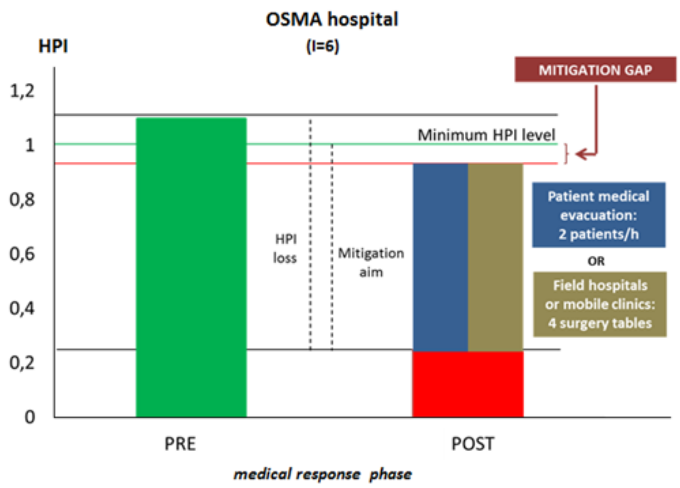

Figure 8.12.: OSMA hospital risk reduction with the application of indirect actions (HPI).

The economic impact of indirect actions is approximately null for the hospital decision makers (with respect to the direct interventions) because the interventions are carried out by other civil and military institutions involved in the medical response chain (chapter 1).

On the other hand, the indirect actions have some negative points, e.g. the transportation of the mobile medical units can't be carried out when the road viability is damaged, which is possible after an earthquake for geological, structural and mass sociologic reasons. Moreover, the mandatory presence of available and undamaged airstrip for airplane and helicopters could make the use of aerial evacuations unavailable.

Finally, the application of indirect measures for mitigating the seismic risk contains an efficiency related problem. Even if the HTCI can reach the appropriate level $HTCI_{TARGET}$, the time necessary to activate a mobile medical unit or the aerial evacuation, which must be quantified as 2 patients every hour, could have significant delays estimated as around 10 hours for fields hospital installation to a couple of hours for urgency medical unit (tents or shelters) [101].

8.2.3. Cost Assessment

The cost of the interventions listed above has been estimated taking into account each mitigation action with the subsequent cost as reported in chapter 4.3.1 and 4.3.2, and by considering the seismic scenario in which they have been contextualized. The cost related to the direct interventions are reported in figure 8.13 and 8.14.

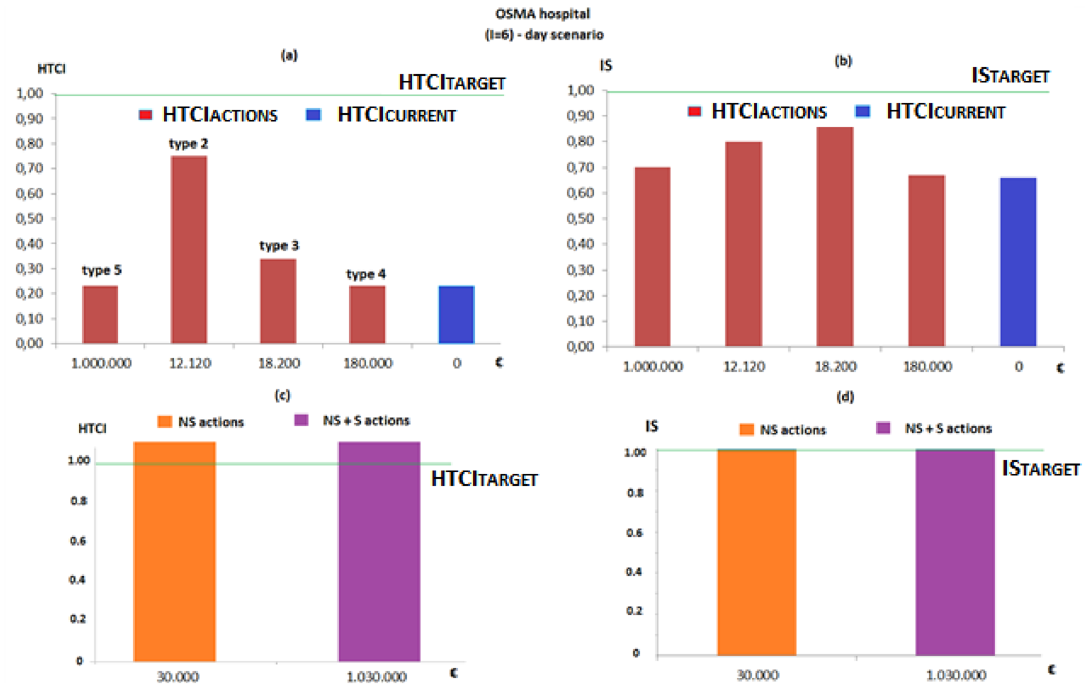

Figure 8.13.: Direct actions' cost for IS_{OSMA} and $HTCI_{OSMA}$: (a)action type-HTCI; (b)action type-IS; (c)Successfully actions-$HTCI_{TARGET}$;(d)Successfully actions-IS_{TARGET}.

- Type 2 and type 3 actions - the interventions pertain to both the technical installations (with fixation techniques, anchorage of functional elements and the inclusion of flexible connections between floors and buildings) and to the medical equipment (anchorage). As OSMA has a total area of 4.838m^2, divided into three main buildings (Lotto 1: 1.800m^2, Lotto 2: 2.688m^{2}and Lotto 3: 350m^2), the estimated total cost of the technical equipment retrofitting is 12.120€. With regards the cost analysis of the medical equipment anchorage, the following procedure has been applied: first, an extraction from the hospital medical equipment database has been asked to clinical engineering department, secondly, the equipment with high-priority of anchorage has been defined according to chapter 4.1 (283 technologies on the whole technology dotation 783 needs anchorage) and as last step the equipment requiring anchorage has been evaluated (182 fixed on 283 with high anchorage priority).

The estimated cost for fixing the remaining 101 devices is 18.200€. Considering both type 2 and type 3 cost, the total assessment for OSMA hospital is around 30.000€.

- Type 4 actions: - in order to simplify the estimation of this intervention, it was taken into consideration the case of the medical personnel essential for working in 1 surgery room which can be approximated to the staff costs: 1 surgeon and 1 anesthetist. The total cost for this scenario is about 180.000€.
- Type 5 actions - as reported in 4.3.1 and 4.3.2, the structural actions are estimated in an expected cost of 200 €/m^2. As the whole surface of OSMA hospital is 4.838 square meters, the subsequent cost can be approximated to 1.000.000€ (4.838m^2 * 200€/m^2= 967.000€).

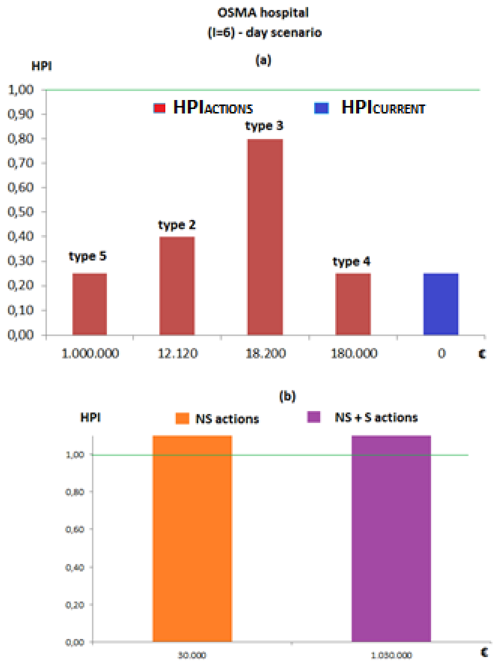

Figure 8.14.: Direct intervention cost related to HPI$_{OSMA}$ according to: (a)type of actions; (b)successful measures.

The cost related to indirect actions are described as follows (fig. 8.15):

- Type 1- according to the type of medical unit used (shelter or tent) different cost are assessed as reported in chapter 4. With regard the OSMA case study, a total cost of 1.660.000€ and 892.000€ is estimated for shelter and tent installation respectively.
- Type 2 – according to chapter 4, the estimated cost for the aerial evacuation of patients is estimated in 10.000€/h, which under the hypothesis of considering only the acute phase of the medical response emergency (first 10 hours), makes the final cost of 100.000€.

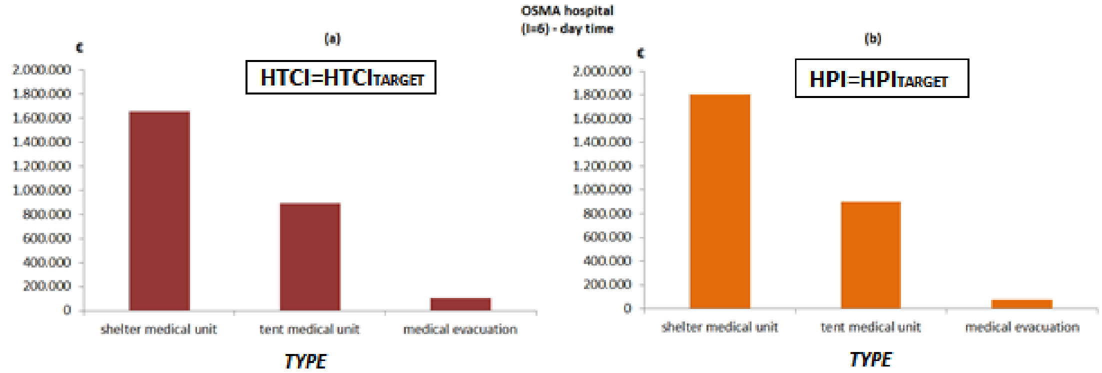

Figure 8.15.: Indirect actions cost for successful mitigation:(a)HTCI and (b)HPI.

8.3. Santa Clara Valley Medical Center (US)

In the following part, the risk mitigation analysis regarding the Santa Clara Valley Medical Center will be described according to the seismic event with seismic intensity I=8. The analysis of the current hospital performance vulnerability is reported in figure 8.16.

Figures 8.16a and 8.16b show the day time current levels for the HTC and IS respectively. The HTC_{TARGET} ($HTC = HTD_{HOSPITAL}$=1.3) is not currently reached and only the half of the medical demand is successfully coped while for the IS_{SCVMC}, a 30% of the whole hospital areas are unsecure.

8.3.1. Direct Actions

Figure 8.17 shows the risk mitigation analysis carried out on IS by the application of the direct actions described in chapter 4. Since the night and day time scenario have the same trends, only the day time scenario will be shown next.

Figure 8.17a reports the simulation according to type 2 actions. Appreciable improvements are detectable for seismic intensities I=5-7 with respect the current situation where the simulated IS could give 90% secure areas. For intensity I=8 the intrinsic security is 80% (10% more than the current value). Finally, for I=9, the simulated IS decreases at 70% and to the minimum value of 60% for intensity I=10.

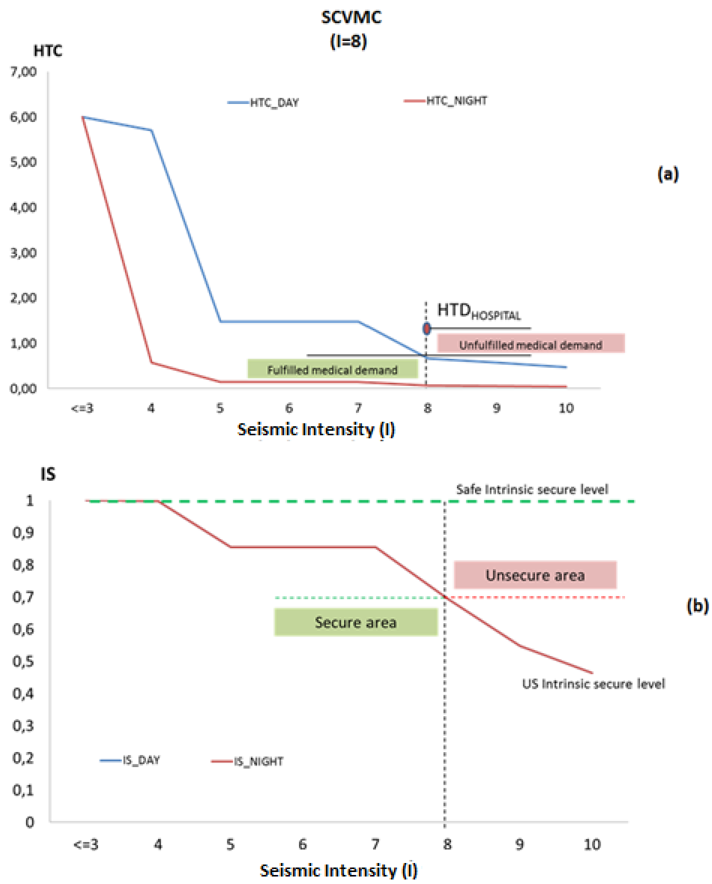

Figure 8.16.: SCVMC performance assessment: (a) HTC and (b) IS.

The application of type 3 actions is reported in figure 8.17b. It shows for I=5-7 an improved value with respect to type 2 actions while for intensity I=8 the levels are similar. For type 4 measures, figure 8.17c reports how there are no mitigation effects for the day scenario. The night/holidays scenario gets the same IS trend than the current day time one. Finally, figure 8.17d shows how type 5 structural retrofitting reports some appreciable effects only at the highest intensities I=8-10.

Figure 8.18 shows the comparison between IS on applying the non-structural actions 'NS' (type 2 and 3 actions) and the non-structural plus the structural measure 'NS+S'. Similar improvements are estimated for both strategies at the seismic range I=5-7 where secure areas are almost the 100% of the whole hospital. For intensity I=8 the structural contribution provides a 5% higher value with respect to the NS strategy: IS=0.9 for NS and IS=0.95 for NS+S. For I=9, the simulated values maintain the same relative differences (IS_{NS}=0.76, IS_{NS+S}=0.8 and $IS_{CURRENT}$= 0.7) while for I=10, the structural contribution provides a 10% higher IS with respect to the 'NS' strategy and almost 100% with regards to the current IS (IS_{NS}=0.68, IS_{NS+S}=0.8 and $IS_{CURRENT}$ =0.46).

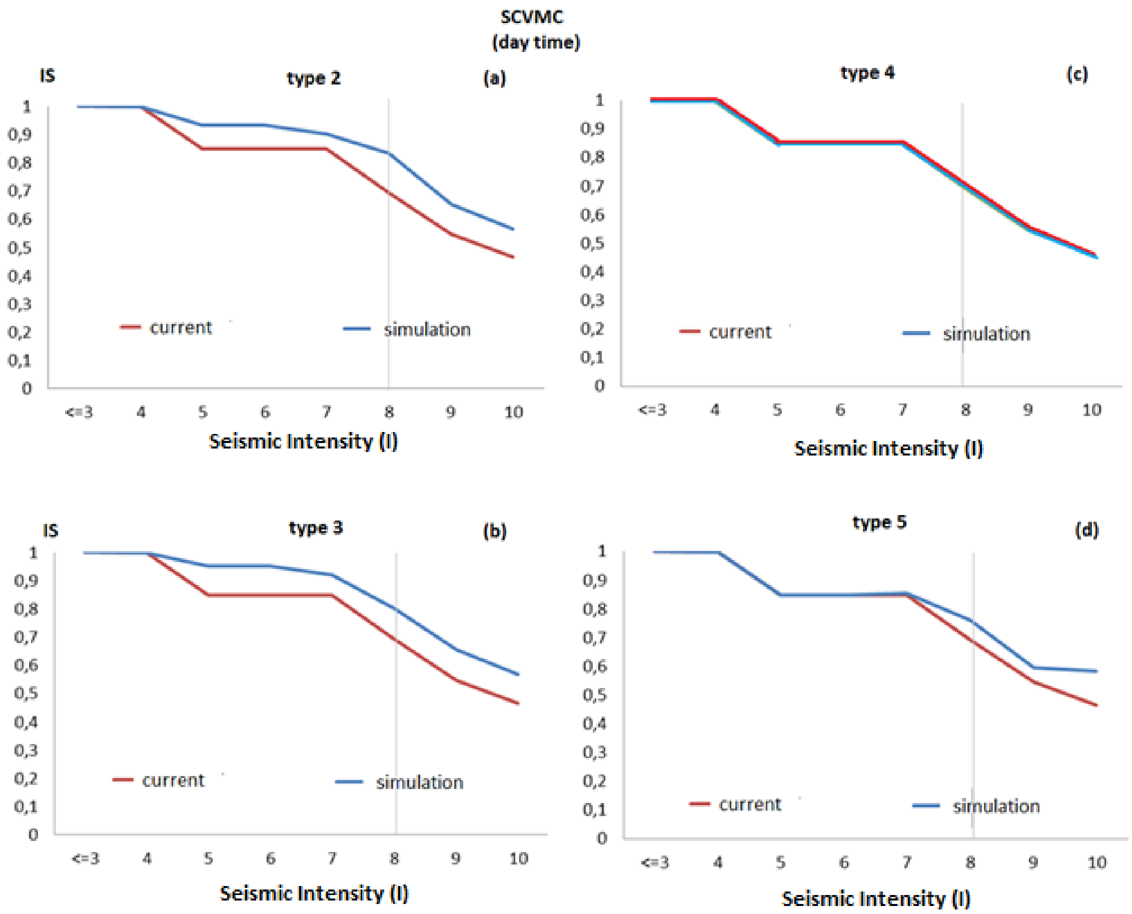

Figure 8.17.: SCVMC risk reduction results on IS according to the retrofitting type for direct actions.

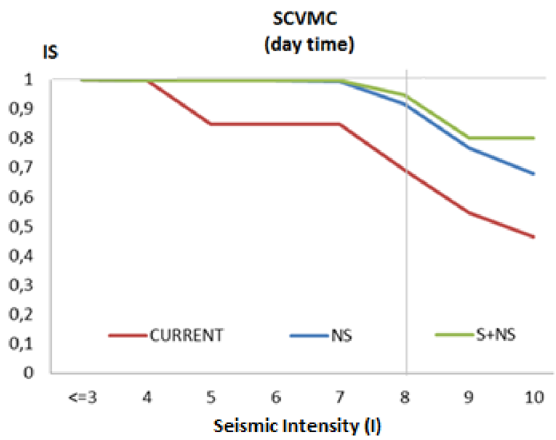

Figure 8.18.: SCVMC risk reduction results on IS according to the retrofitting strategies ‘NS’ and ‘NS+S’.

With regards to the HTC, figure 8.19a shows the comparison between the current situation and the simulation according the type 2 actions for the day scenario. It shows appreciable improvements for the seismic intensities I= 5-7 (+1.03) while for highest intensities the improvements are lower but still perceptible with a medium increase of 0.25.

Moreover, figure 8.19b shows the effects of the type 3 actions. The simulated improvement of for intensities I=5-7 is about of 214% with respect to the current situation while lower but still high improvements are observed for the seismic intensity I=8 – 10 which shows an increase of 167% for magnitude I=8 and 121% for I=9 -10.

No improvements are registered for the day time HTC according to type 4 actions (figure 8.19c) while figure 8.19d shows the effects of the structural retrofitting (type 5 actions) and reports appreciable improvements with respect to the current values estimated for the intensity I=10 (+21%).

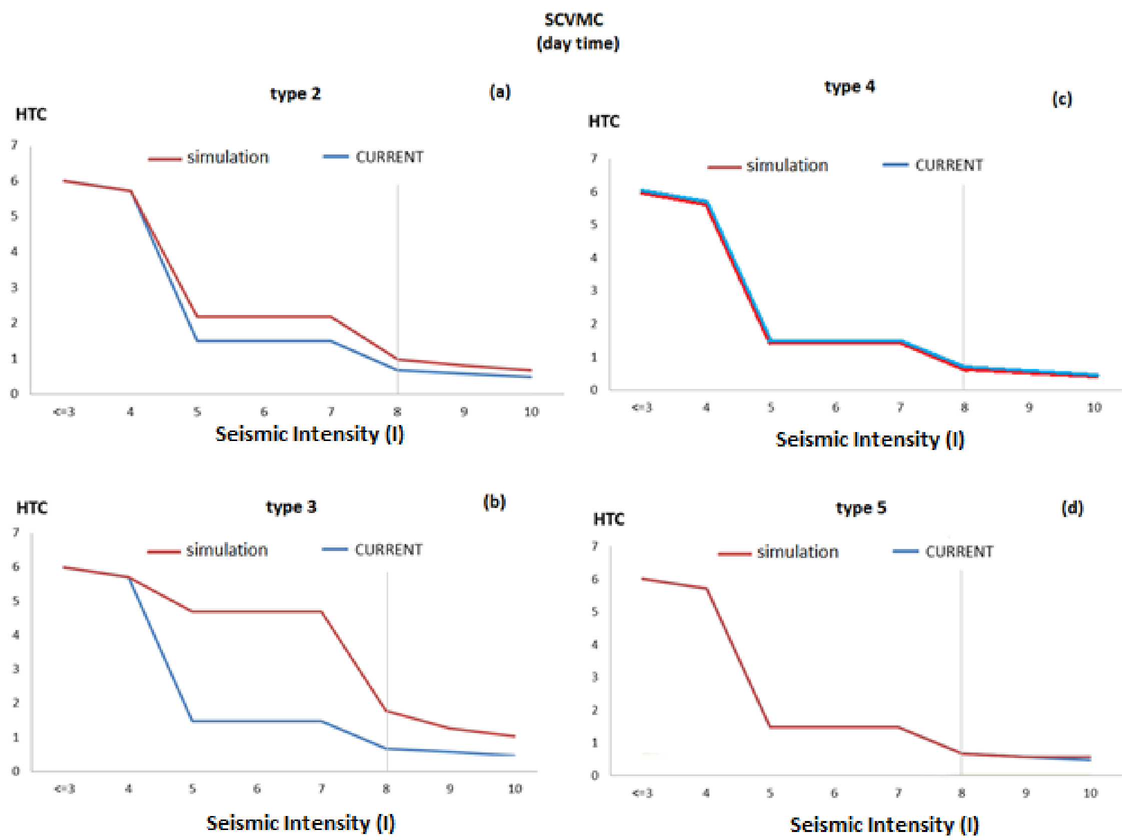

Figure 8.19.: SCVMC risk reduction results on HTC according to the retrofitting type for direct actions.

Figure 8.20 shows the effects of mitigation strategies 'NS' (type 2+ type 3 actions) and 'S+NS' (type 2+ type 3 + type 5 actions) on HTC. The only difference existing between the two strategies is only appreciable for intensity I=10 which reports an improvement with respect of the current situation of 280% for 'NS+S' and 223% for 'NS'. For all the other seismic intensities (I=3-9) both simulations show similar values. For the seismic range I=5-7, the simulated value is constant (HTC=6.0) while for I=8-9 a 223% improvement is estimated with respect to the current situation.

The structural retrofitting for the US case study permits to improve the HTC only for the highest seismic intensity I=10 by showing a 20% improvement with respect to 'NS' mitigation. Moreover, the smaller impact of structural retrofitting for HTC_{SCVMC} than for IS_{SCVMC} is justified by the location of the surgical area which is entirely situated in a steel moment resistant building while the inpatients wards are shared between a steel building and the old wing area built before 1980.

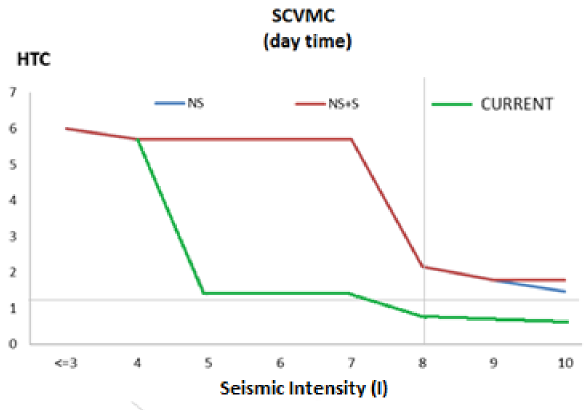

Figure 8.20.: SCVMC risk reduction results on HTC according to the retrofitting strategies 'NS' and 'NS+S'.

With regards to the SCVMC response to the impact, figure 8.21 shows the current HTCI pre- and post-event (I=8) degradation for the day scenario. The pre-event HTCI (4.67) is reduced to the HTCI=0.52 which is not enough for a successful medical response of the health structure.

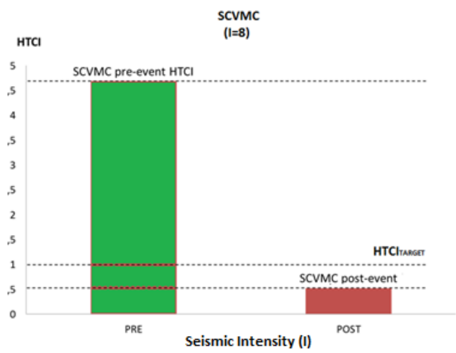

Figure 8.21.: HTCI reduction due to seismic impact at SCVMC.

Next, as well as done for the IS, the effects of the different mitigation actions on HTCI are reported for both day and night/holidays scenarios.

Figure 8.22a shows the effects by applying type 2 actions. A 46% improvement has been assessed for both day and time scenario while the effects of simulating the type 3 actions provides a 165% improvement for both day and night scenario with respect the current situation, see figure 8.22b. Figure 8.22c shows the effects by applying the type 4 measures. No improvements are estimated for the day scenario while for the night one a 868% improvement has been assessed ($HTCI_{NIGHT}$=0.53). Finally figure 8.22d reports the effects of type 5 actions. No appreciable improvements have been assessed for the seismic level I=8 for both day and night scenario.

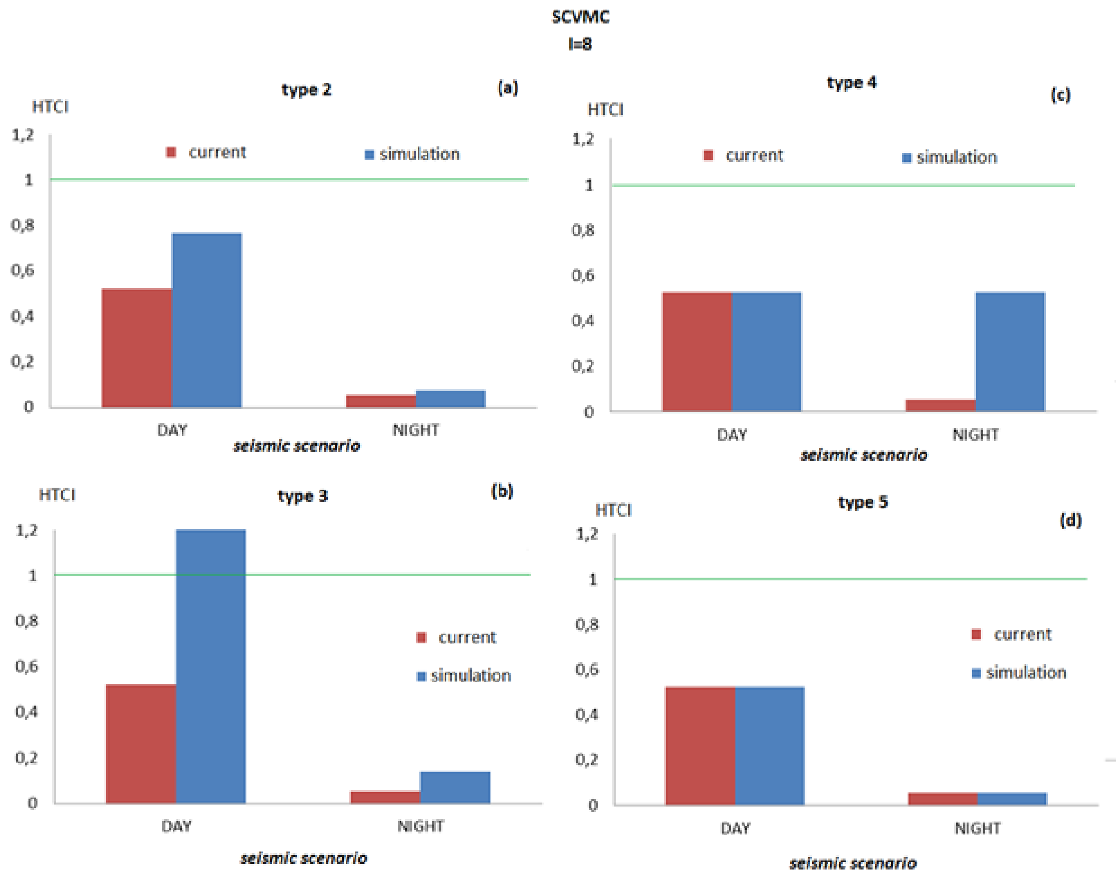

Figure 8.22.: SCVMC risk reduction results on HTCI according to the retrofitting type for direct actions.

Figure 8.23 shows the comparison between the simulated retrofitting of non-structural 'NS' strategy and "non-structural and structural actions" (NS+S) with respect to the current situation. The $HTCI_{TARGET}$ for successfully coping with the medical demand in the aftermath of an earthquake (I=8) is obtained by both strategies (NS and NS+S). The structural retrofitting is unnecessary for a seismic intensity I=8 event.

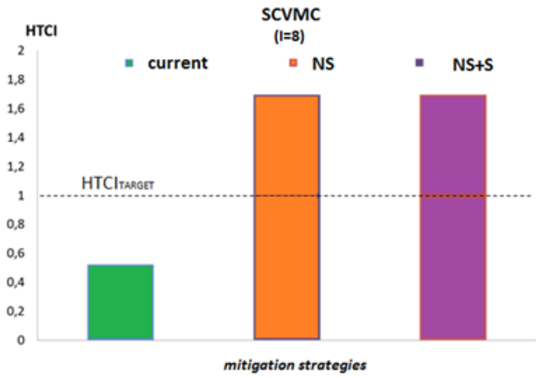

Figure 8.23.: HTCI risk reduction according to retrofitting strategies 'NS' and 'NS+S'.

Figure 8.24 shows the results of simulating the retrofitting actions defined above.

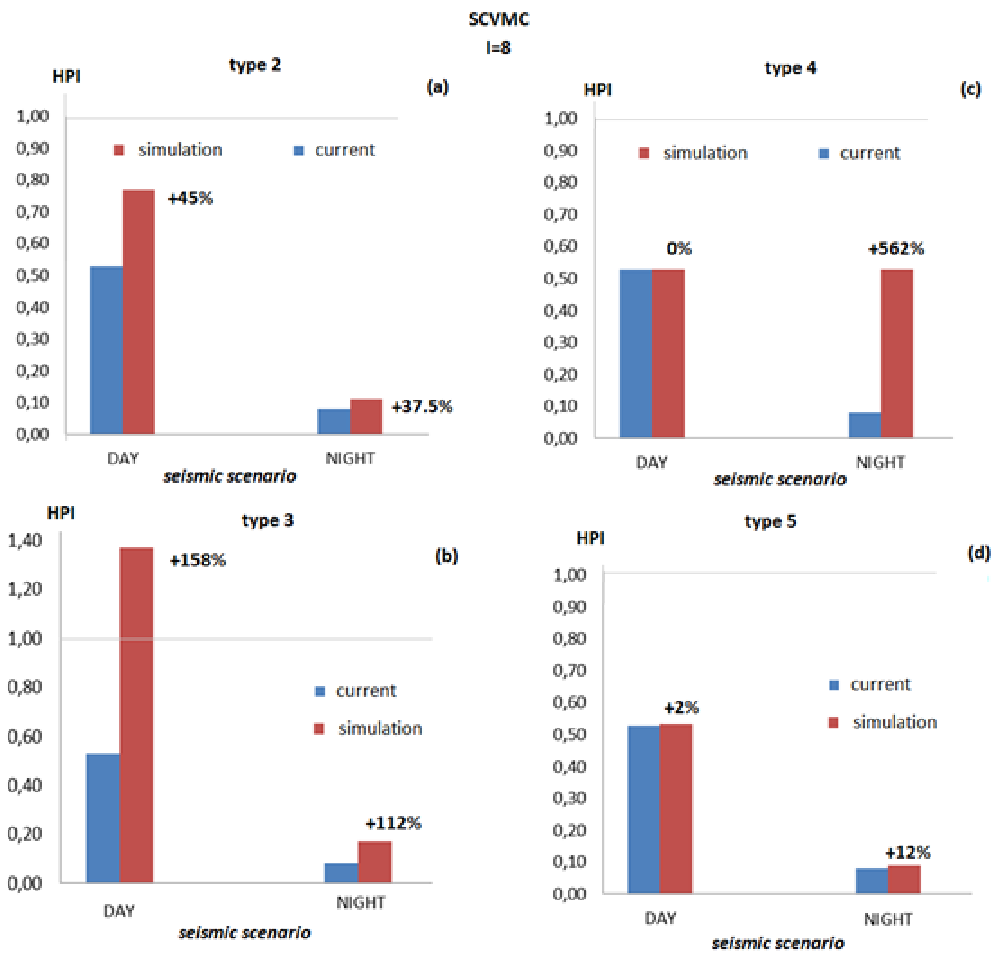

Figure 8.24.: SCVMC risk reduction results on HPI according to the retrofitting type for direct actions.

According to the current HPI, the mitigation aim for both scenarios day and night is providing HPI_{EXTRA}=0.47 and HPI_{EXTRA}=0.91 respectively. In other words, the goal is keeping the maximum acceptable HPI loss within the value 2.21 ($HPI_{pre\text{-}event}$-HPI_{TARGET}).

Figure 8.24a simulates the effects of seismic retrofitting with type 2 actions. With regards to the current HPI, improvements of 45% and 37.5% have been assessed for both day and night/holidays scenarios respectively. Figure 8.24b reports the type 3 retrofitting simulation. Improvements of 158% and 112% with respect to the current HPI have been estimated for both day and night/holidays time scenarios respectively. Figure 8.24c shows the effects on type 4 actions. No improvements are estimated for the day scenario while for the night scenario a 562% upgrade has been evaluated. Finally figure 8.24d reports the simulation with the type 5 retrofitting which shows light improvements with respect to the current situation: 2% and 12% for day and night scenarios respectively.

Figure 8.25 shows the comparison between non-structural (NS) and the structural plus non-structural (S+NS) strategies with respect to the current situation. Both seismic scenarios have been analyzed without taking into consideration the type 4 actions. For the day scenario structural retrofitting are unnecessary for reaching the HPI_{TARGET} at the level I=8 since the total improvement obtained with NS strategy for daytime provides with a simulated HPI= 1.65 (+215%). For the night scenario, although the simulation results for both strategies show improvements with respect to the current one, the HPI_{TARGET} is far away to be obtained.

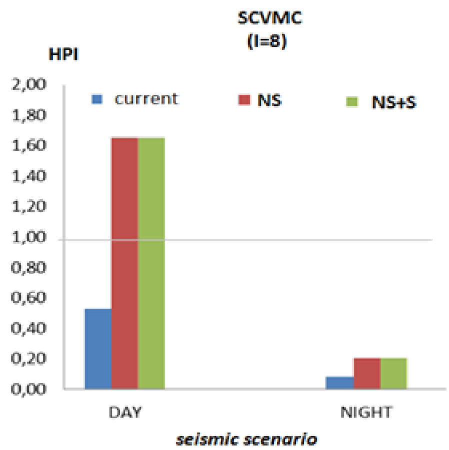

Figure 8.25.: SCVMC risk reduction results on HPI according to the retrofitting strategies ‘NS’ and ‘NS+S’.

8.3.2. Indirect Actions

The results of seismic risk mitigation with the use of indirect actions are reported as follows. The current HTCI (0.52) means that only half of the medical demand can be satisfied and in order to get the $HTCI_{TARGET}$, indirect interventions must guarantee improvements able to get an extra HPI of 0.48. This corresponds to a HTC_{EXTRA}=0.63 (HTC=$HTD_{HOSPITAL}$).

According to the immediate post-event phase, 1.5 extra surgery tables are necessary for an appropriate hospital response. Because of the fact that it is not possible providing with 1.5 extra surgery tables, figure 8.26 shows the retrofitting scenario obtained with 2 extra surgery tables. Moreover, figure 8.26 reports the mitigation effects obtained by the use of aerial medical evacuation which is estimated in 1 patient per hour.

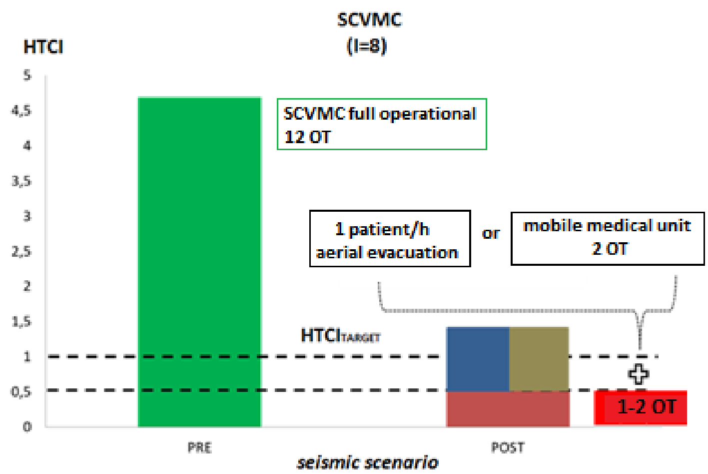

Figure 8.26.: SCVMC hospital risk reduction with the application of indirect actions (HTCI).

Regarding the intrinsic security (IS), no indirect intervention can improve it because this index evaluates the security within the hospital before the event.

Finally the post mitigation HPI is reported in figure 8.27. The compliance with the HPI_{TARGET} is due to the fact that both the type 1 and type 2 indirect actions were chosen bigger than the ones suggested by the mathematical calculations (2 tables instead of 1.5 and 1 patient evacuated per hour instead of 0.5). The use of precise values beside the impossibility to operate on the intrinsic security through the indirect interventions would have given a post mitigation HPI=0.96.

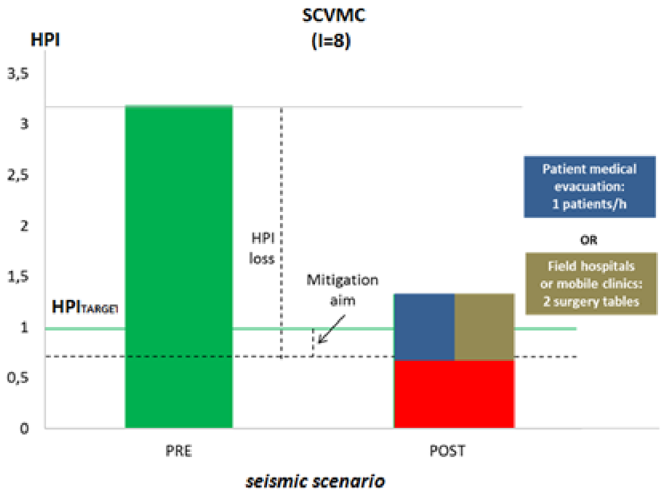

Figure 8.27.: SCVMC hospital risk reduction with the application of indirect actions (HPI).

The cost assessment for indirect actions can be assumed null for the hospital decision makers with respect of the direct interventions because the interventions are carried out by other civil and military institutions involved in the medical response chain (chapter 1).

On the other hand, the indirect actions have some negative points such as the transportation of the mobile medical units which can't be carried out when the road viability is damaged. This could be possible when after an earthquake for geological, structural and mass sociologic reasons. Moreover, the mandatory presence of available and undamaged airstrip for airplane and helicopters could make the use of aerial evacuations unavailable.

Finally, the application of indirect measures for the seismic risk mitigation reports efficiency related problem. Even if the HTCI can reach the appropriate $HTCI_{TARGET}$, the time necessary to activate a mobile medical unit or the time necessary to the aerial evacuation, which must be quantified as 2 patients every hour, could have significative delays which can be estimated around 10 hours for fields hospital installation to a couple of hours for medical units (tents or shelters) [101].

8.3.3. Cost Assessment

The costs related to the interventions listed above were estimated by taking into account the analysis in 4.3.1 and 4.3.2 and contextualized to the SCVMC case. The estimations according to the direct interventions are reported in figure 8.28 and 8.29 as follows:

- Type 2 and type 3 actions - the interventions pertain to both the technical installations (functional elements anchorage and the inclusion of flexible connections) and medical equipment (anchorage of medical devices). From a point of view of the technical plants, the whole SCVMC area must be considered (68.000 m2). The estimated total cost of type 3 actions is approximately 170.000€. For type 2 actions cost estimation, the following operating procedure was applied:

1. Definition of the medical equipment with high-priority of anchorage according to chapter 4.1;

2. Field inspection and personnel interviews for the anchorage evaluation of high priority anchorage medical equipment. From the analysis, some technologies were not properly anchored to the ground, see table 8.1. Unfortunately, it was not possible to obtain the technology database of SCVMC, so in order to have the total numbers at the SCVMC, a projection on the whole number of medical device according to the technology proportions of OSMA hospital was chosen. The estimated number of devices which need to be fixed is 88, which corresponds to an expected cost of 13.000€.

High priority anchorage technology unfixed to the floor
ANAESTHESIA SYSTEM
ULTRASOUND DEVICE
ELECTRO SURGICAL INSTRUMENT
INCUBATOR

Table 8.1.: Unfixed technologies found at the SCVMC.

- Type 4 actions – the same procedure as for the OSMA hospital has been followed which shows an estimated cost of 180.000€, see paragraph 8.1.3.

- Type 5 - as reported in paragraphs 4.3.1 and 4.3.2, the structural interventions are estimated for a total cost of 200 €/m^2. Although the total surface area of the SCVMC is 68.000m^2, the cost estimation of the structural retrofitting can be evaluated by considering only the buildings "b" and "c" which contain the medical areas essential to the performance and response (44.826m^2) and evaluated as approximately 9.000.000€ (44.826m^2 * 200 €/m^2 = 8.965.200€), see figure 8.28.

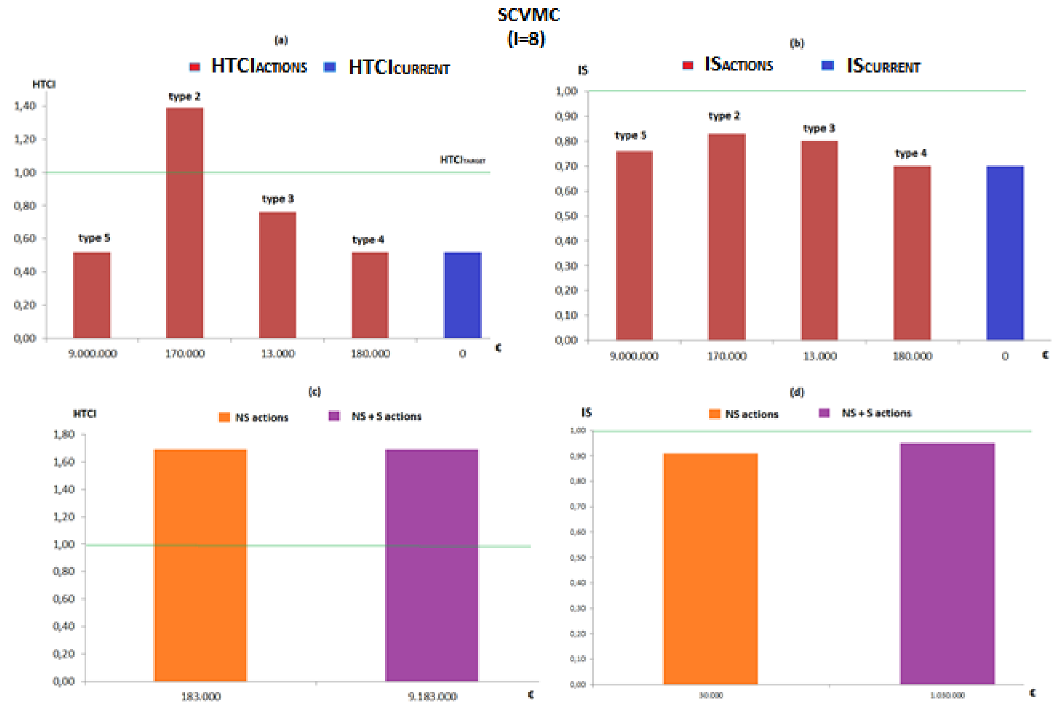

Figure 8.28.: Direct actions costs for IS and HTCI according to: (a)type of actions (HTCI); (b)type of actions (IS); (c)successful actions ($HTCI_{TARGET}$); (d)successful actions (IS_{TARGET}).

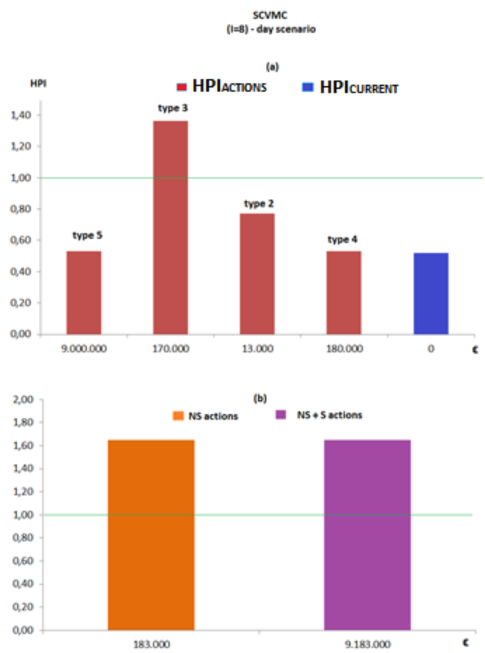

Figure 8.29.: Direct intervention costs related to $HPIS_{SCVMC}$according to: (a)type of actions; (b)successful measures.

The cost related to the indirect intervention are described as follows, see figure 8.30:

- Type 1- according to the type of medical unit used (shelter or tent) different cost are assessed as reported in chapter 4. With regards the SCVMC case study, a total cost of 678.000€ and 446.000€ are estimated for shelter and tent installation respectively;

- Type 2 – according to chapter 4, an estimated cost for the aerial evacuation of patients can be estimated in 5.000€/h, which is in total 50.000€ according to the hypothesis of considering only the acute phase of the medical response emergency (first 10 hours).

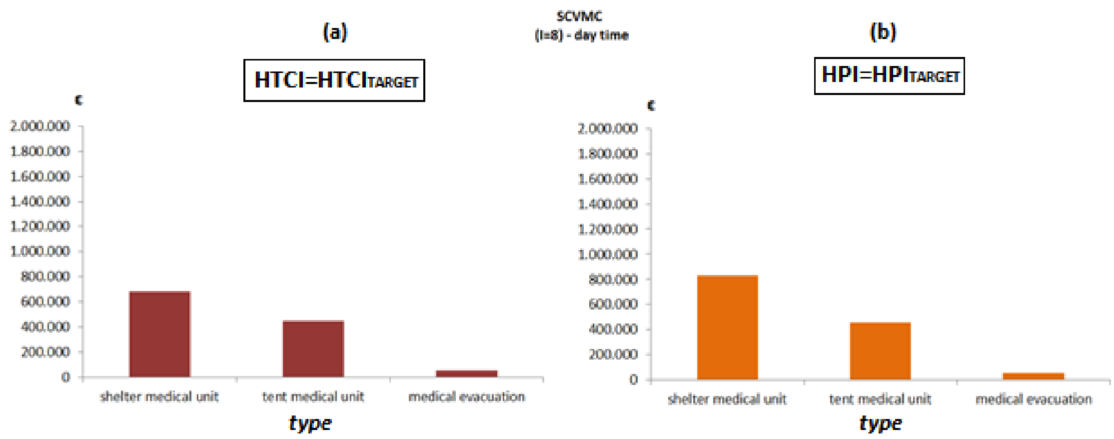

Figure 8.30.: Indirect intervention costs for successful mitigation related to (a)$HTCI_{SCVMC}$ and (b)HPI_{SCVMC}.

8.4. OSMA - SCVMC Comparison

Both OSMA hospital and SCVMC direct actions are able to get the HPI_{TARGET} for the risk mitigation. The structural interventions (Florence at I=6 and US at I=8) do not provide any further improvements to the simulated HPI obtained with the application of only non-structural interventions, see figure 8.31.

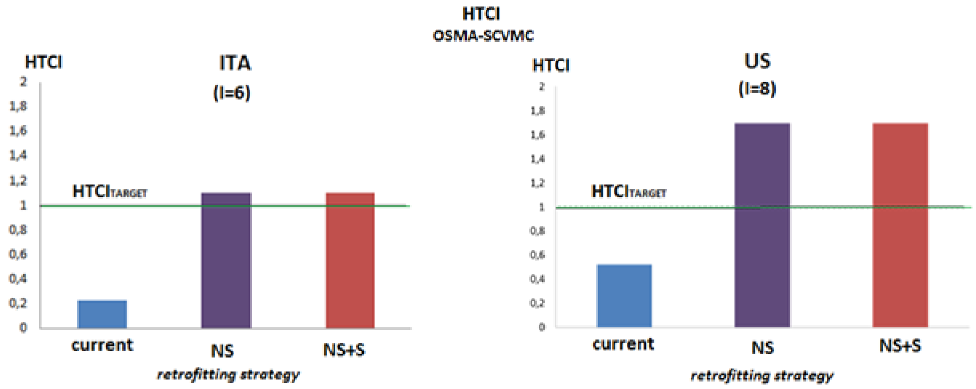

Figure 8.31.: HTCI comparison between the OSMA hospital and SCVMC case studies.

Moreover, within the non-structural interventions, type 3 actions are the most effective for the risk reduction in both hospitals, see figure 8.32 even if they are not enough to get $HTCI_{TARGET}$ at OSMA hospital. It can be only obtained by the simultaneous application of both type 3 and type 2 actions. Because of the high difference in the hospitals areas (about 5.000m^2 for OSMA and 68.000m^2 for SCVMC), despite the necessity of more interventions for OSMA the cost for US mitigation are estimated much more expensive than for the Florentine hospital: 170.000€ for SCVMC and 30.000€ for OSMA hospital.

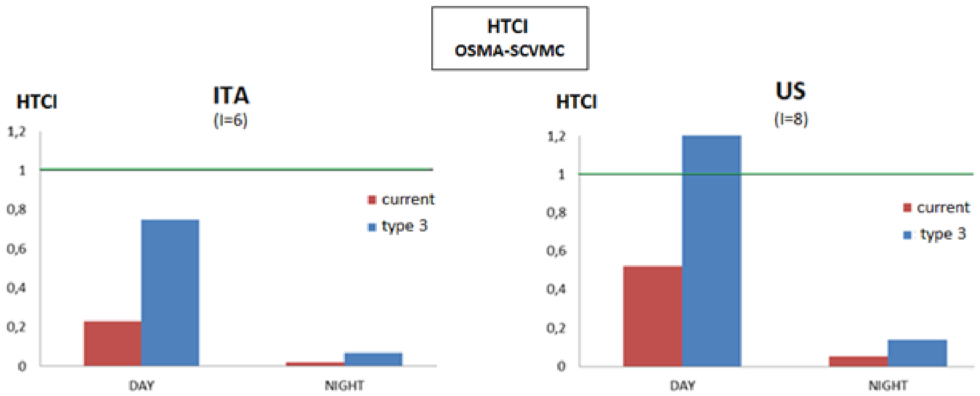

Figure 8.32.: Retrofitting effects on HTCI by applying type 3 actions to both OSMA hospital and SCVMC.

Regarding the HPI post mitigation, in both case studies the direct mitigation interventions are able to get the HPI_{TARGET}, see figure 8.33. As well as for the HTCI, structural interventions do not provide appreciable further improvements to the OSMA and SCVMC hospitals with respect to the application of non-structural interventions only.

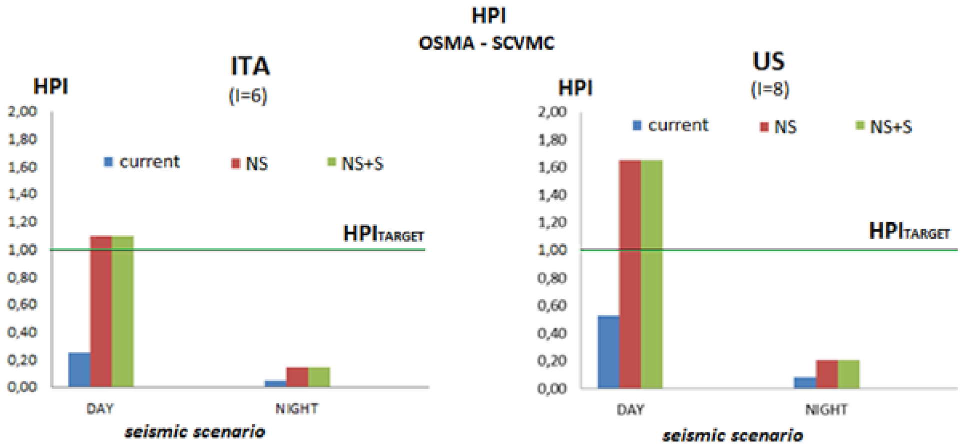

Figure 8.33.: HPI comparison between the OSMA hospital and SCVMC.

As reported for the HTCI comparison, the HPI analysis shows how basic installation retrofitting is enough to obtain appropriate seismic risk mitigation for the US case study while for the Italian application both the equipment and basic installation retrofitting actions are necessary to reduce the seismic risk (I=6). Moreover, $HTCI_{TARGET}$ and HPI_{TARGET} can't be reached for the night scenarios in both applications. Only the simultaneous intervention of types 3-4 for US and types 2-3-4 actions for OSMA, will be effective to get the HPI_{TARGET} and $HTCI_{TARGET}$ in the night/holidays.

Finally, with regards to the indirect mitigation procedure, figure 8.34 reports both applications to the Italian and US case studies.

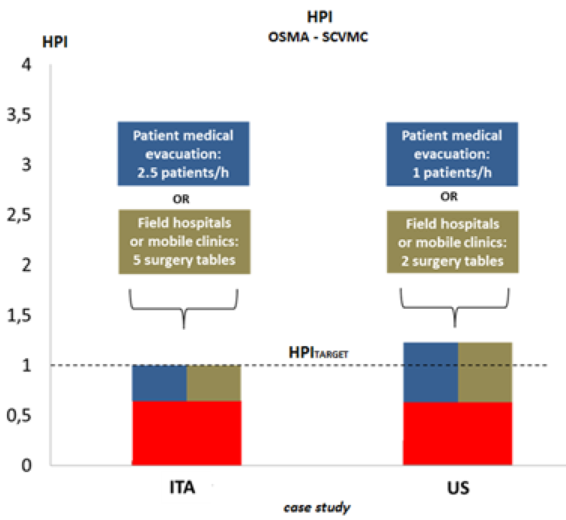

Figure 8.34.: HPI comparison between indirect interventions at both the OSMA hospital and SCVMC.

Less external facilities and medical evacuation of patients are essential in order to get the HPI_{TARGET} at the SCVMC compared to the Italian study: 2 extra surgery tables and 1 patient/h aerial evacuation are half of the total support necessary to OSMA. Moreover, the application of indirect interventions for the risk mitigation of the US hospital is cheaper than the OSMA hospital in Florence, see figure 8.35. The cost of indirect interventions for HTCI are similar to those for HPI.

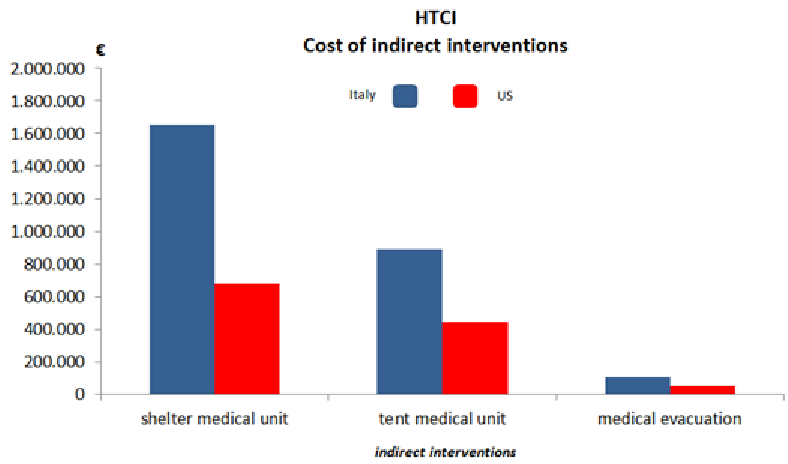

Figure 8.35.: HTCI (or HPI) cost analysis of indirect actions application to OSMA hospital and SCVMC.

9. The DSS prototype

9.1. Overview

This last chapter describes the development of an informative prototype of a Decision Support System (DSS) for carrying out seismic assessment and mitigation simulations within health structures. An efficient risk mitigation model is the one which is usually apply from stakeholders. Usability aspects are essential for providing important information to the decision makers which must be immediate, fast and clear in order to properly support the decisions.

9.2. Risk Technology as Risk Dissemination

In chapter 2, ISO 31000:2009 states that the communication of risk essential to fully understand the risk connection with the context, communication and consultation with internal and external stakeholders. Moreover, within the communication of risk different steps and stages are defined as the phase of support for a treatment plan. An appropriate risk management method is given when the responsible decision makers are basing their decision on the model itself. Communication to the decision level and developing supporting tools/instruments become essential for the whole risk mitigation methodology. For this reason technology should be applied for the development of this tool by providing the most friendly and accurate systems.

The basic ideas which are at the base of the following DSS are usability [103] and clearness of the information and simulation approach.

Usability is important to guarantee the use of the system by the decision maker which gets a good feedback and perception in the system application. Clearness of the information is extremely important in complex system's analysis because of the presence of numerous data and statistics which make the decision step really confusing. Choosing a few but important information according to a priority scale is essential to the decision effectiveness and rapidity. Lastly, the simulation approach is fundamental to the decision makers to easily compare and understand the simulated effects of different choices and scenarios, especially for complex systems such as hospitals where the effects of an intervention in a specific part of the system is difficult to be predicted.

9.3. DSS Prototype

The aim of prototyping an informative system such as the DSS resides in the technical specification provision as well as the functional and logic structure of the system beside the user interface (essential for the usability aspect) and the accesses' (permissions, privacy and login-logout) polices.

In the next section the prototyping aspects of the DSS for risk management in hospitals will be described especially with regards to the functional and logical structure, the accesses policy and the user interface development. The technical specifications are not deeply analyzed here since they strongly depend on the type of programming language used for the system implementation such as java, php, asp, c++, visual basic etc.

9.3.1. Software Mock-up as Technology Prototyping

Software prototyping is mainly based on two major types of prototyping: Throwaway Prototyping and Evolutionary Prototyping [102].

Rapid prototyping

The throwaway prototyping or Rapid Prototyping refers to the working model of the system which is mainly developed to visually show the users what their requirements may look like when they are implemented into a finished system.

Advantages in using a rapid prototyping are the rapidity, the efficiency and the cost-effectiveness of the informative system validation in terms of quality suggestions for functional and usability software requirements.

Evolutionary prototyping

The Evolutionary Prototyping's main goal is to build a very robust prototype in a structured manner and constantly refine it. This approach allows the development of new features which couldn't be conceived at the design phase.

Moreover, although this method takes long in the whole application process from a technical point of view it only takes into consideration already functional systems which can be used as important basis for the final product.

Mock-up and Prototype

According to the ISO technical report ISO/IEC TR 14759:1999 (Information technology - software engineering: Mock up and prototype, a categorization of software mock up and prototype models and their use) [104], mock up and prototypes are technical terms which are different but commonly confused. A software mock up can be defined as a provisional product that cannot be used by users neither intended to evolve into a fully operational product (verification, training and recording aims) while a software "prototype" represents already a part of the target product which may evolve into an operational product.

As reported by the ISO/IEC technical report [104] it is important to make an additional distinction on software prototyping methods according to the specific features of software aims:

- Illustrative - related to realistic graphic representation (Human Computer interface);
- Functional - capable of performing computations.

Moreover, the prototype development is essential for reducing risks of critical projects such as the supporting tools for decision making process in risk management for healthcare [104-106].

The mock up makes part of the rapid prototyping techniques and it does not provide a real version but a realistic version of the target product which is characterized by the following features [104]:

- Not all features of the target product need be represented;
- The development environment (machine, language, and tools) need not be that of the target product but it must be representative of the target product;
- The operating environment technical components need not be those of the target product but they must be representative of the target product;
- It is acceptable to use a subset of the documentation normally used to document the full development life cycle.

9.3.2. Description of the System

A HTML based software has been used for developing a demonstrative functional mock up (typical for rapid prototyping) in order to show the functional organization of a seismic risk management decision support system for hospitals.

The DSS, based on the methodology and models reported in the previous chapters, is showed in figure 9.1 and based on three main functions: new project and open projects for the users and the database management for the system administrator.

Figure 9.1.: Homepage belonging to the mock-up of the seismic risk management in hospital DSS 'SIRIO'.

The seismic risk management applied to hospitals consists of three activities, the vulnerability assessment, the risk analysis and the risk mitigation. The choice of one of this assessment is requested once an old projects is open either when a new project is named, see figure 9.2.

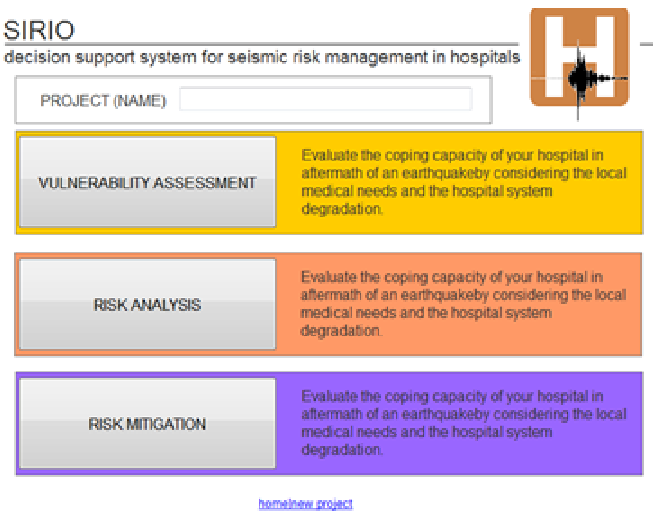

Figure 9.2.: SIRIO DSS – the risk management activities.

For the seismic vulnerability assessment, included as first step in all the other activities, the data inserting includes, besides the general info, the structural aspects (figure 9.3a) and non-structural data (figure 9.3b). Within the no-structural data, the following technical systems are reported: medical gas, power distribution, fire system, plumbing infrastructure, medical equipment, hospital IT, internal viability and external accessibility, air system and administrative/organizational.

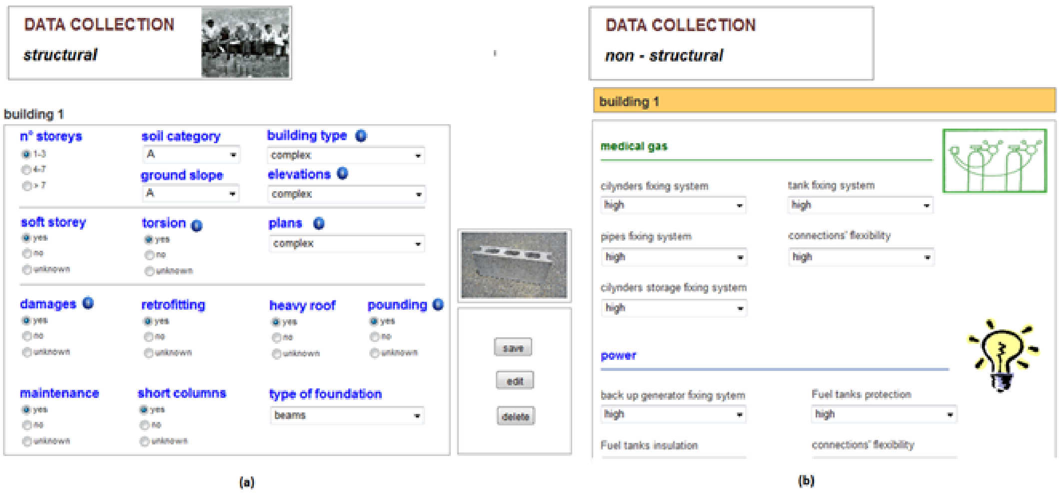

Figure 9.3.: SIRIO DSSS - Data inserting forms.

For the risk analysis data and information on the seismic scenario are requested. In fact figure 9.4 reports the data input form which defines as necessary information the expected seismic magnitude, number of local hospitals and number of expected injuries.

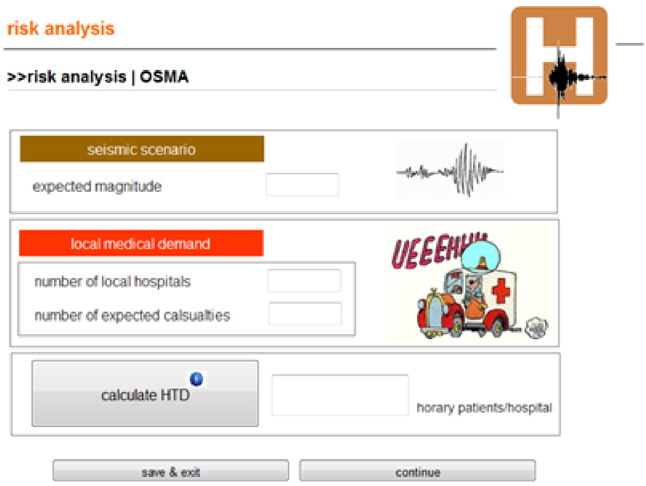

Figure 9.4.: SIRIO DSS – risk analysis form.

With regards to the risk mitigation phase, the DSS gives two possible interventions: direct and indirect ones. A list of each possible action belonging to the type of interventions is reported for both categories, see figure 9.5.

The results are expressesed by showing both the estimated situation according to the current collected data and the simulated one which includes the retrofitting cost as well.

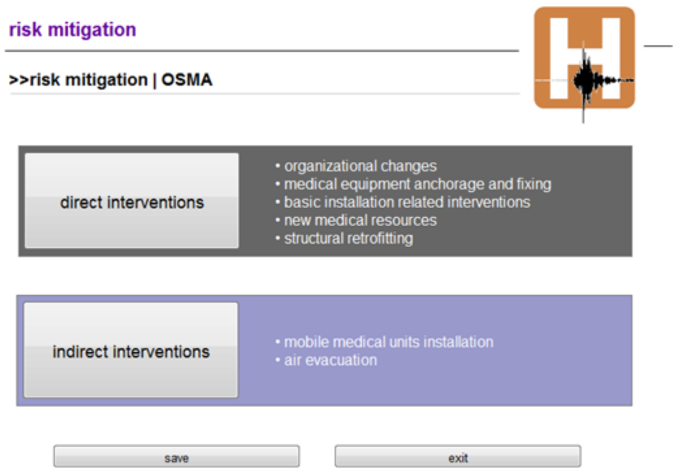

Figure 9.5.: SIRIO DSS – the risk mitigation page: direct and indirect interventions.

Finally figure 9.6a and 9.6b show the model when "open a project" or "my Database" action is chosen respectively. While for the "open a project" action the user is allowed to open, delete or edit the different saved projects, for the DB management only the system administrator is allowed to enter through a protected login asking for username and password. The possible actions permitted in the DB management section are the modification of the structure/data of each project and the extraction of the DB containing the hospital and scenario data inserted by the users.

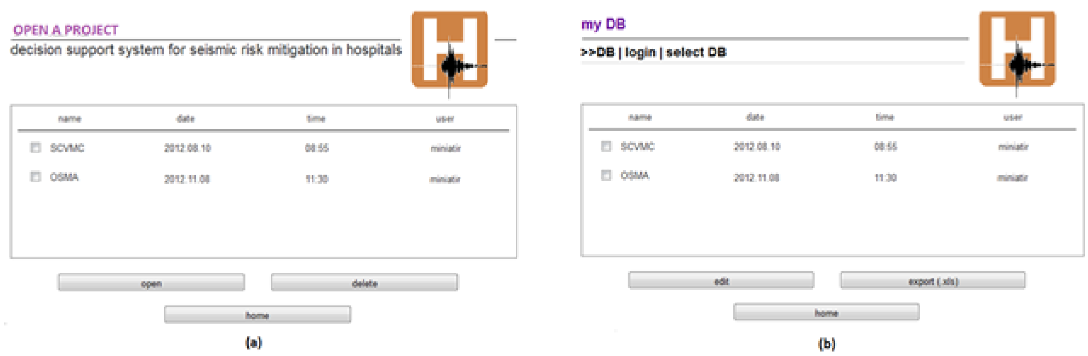

Figure 9.6.: SIRIO DSS – (a)open a project form; (b)front end section for the DB management.

10. Conclusions and Further Developments

Local hospital response is one of the essential key points of the medical response to an earthquake. According to the international state of art of risk management in hospitals, the methodology proposed by this work consists of an integration of typical approaches: the rapid vulnerability assessment and the critical infrastructure modeling.

This allows a complete analysis of structural, non-structural (including the new forms for the fire safety and medical equipment vulnerability assessment), organizational aspects and their connections within the complex system given by the health facility, all of which are indispensable to guarantee an efficient and safe response by hospitals.

Moreover, a new index of intrinsic security (IS) is defined alongside the hospital treatment capacity (HTC) which allows the evaluation of both the strategic and sheltering function of health structures while the new Hospital Performance Index (HPI) summarizes the hospital response to the seismic impact on the local scenario by the estimation of the expected medical demand and hospital performances degradation.

Once the methodology has been developed, the application of a sensitivity analysis shows that the Fault Tree Analysis approach provides a more reliable behavior and more accurate outputs than the Leontief model, as observed in the methodology validation at the main hospital during L'Aquila earthquake (Ospedale San Salvatore, April 6, 2009).

The risk mitigation in Italy (OSMA hospital) and in US (SCV Medical Center) shows similarities and interesting differences. For both cases structural retrofitting is unnecessary for the risk reduction and the seismic risk is higher for the night/holidays scenario since the effective performance of the medical personnel, which is mostly available on call, may depend on their housing resilience and the availability of road viability during earthquakes.

The main differences result from the non-structural retrofitting actions. Basic installation elements' anchorage is enough for an appropriate hospital response in the US case study while for the Italian one this must be added to further anchorage of the medical equipment. Moreover, the use of indirect interventions (installation of mobile medical units and aerial medical evacuation) is estimated to be half demand for the Californian hospital compared to the Florentine facility.

Although fewer interventions are required for the US hospital, the estimated cost are evaluated as much higher than the Italian hospital. This is due to the different sizes of the facilities (70.000$m^2$for the SCVMC and 5.000$m^2$for OSMA hospital in Italy).

Finally the prototyping process for developing the informative decision support system (DSS) has been carried out in order to improve the dissemination of the methodology and aims to provide the usability and functional specifications essential for hospital risk management DSS.

Further developments are needed to analyse the other elements involved in the medical response in aftermath of earthquake such as the building structural resilience, the road net infrastructure analysis and evaluation on the rescue and search activities.

Finally the simulation oriented approach of the model could also be applied by the civil protection decision makers for planning (and optimizing resources) a synergic and systemic risk management response which could include all the local hospitals' response according to the specific characteristic of each medical facility.

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